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# FILAMENT COMPOSITE MATERIAL LANDING GEAR PROGRAM, VOLUME I

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# FILAMENT COMPOSITE MATERIAL LANDING GEAR PROGRAM

## VOLUME I

*THE BENDIX CORPORATION*
*ENERGY CONTROLS DIVISION*



TECHNICAL REPORT AFFDL-TR-72-78





AIR FORCE FLIGHT DYNAMICS LABORATORY
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

234

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13 ABSTRACT


The objective of this program was to explore the utility of boron composite materials in aircraft landing gear construction. The contract work statement required the design, fabrication and test of a boron composite material landing gear assembly interchangeable in both geometry and performance with the main landing gear of the A-37B aircraft.

The use of BORSIC$^{R}$-aluminum and boron epoxy materials was explored. Hardware designs were evolved for both materials. The BORSIC$^{R}$-aluminum components were fabricated by Hamilton Standard and the boron epoxy components by Hercules, Inc.

One full size landing gear assembly was tested. This assembly was composed of a boron epoxy outer cylinder, inner cylinder and side brace. All attachment fittings were metallic. The assembly was tested for hydraulic pressure containment and static structural strength in the Bendix laboratories.


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# FILAMENT COMPOSITE MATERIAL LANDING GEAR PROGRAM

## VOLUME I

*THE BENDIX CORPORATION*
*ENERGY CONTROLS DIVISION*
*SOUTH BEND, INDIANA 46620*

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I-2

# FOREWORD

This report presents the work accomplished during the period of 1 April, 1969 to 1 April, 1972 on USAF Contract No. F33615-69-C-1558, Project No. 1369.

The program is sponsored by the Air Force Flight Dynamics Laboratory, Research and Technology Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. Capt. G. Shumaker, FEM, was the Program Manager.

The program prime contractor was The Bendix Corporation, Energy Controls Division and the program subcontractors were Hamilton Standard Division of United Aircraft Corporation, and the Chemical Propulsion Division, Hercules Incorporated. Performance of this contract was directed for Bendix by A. L. Courtney, program management and R. V. Cervelli, technical director. Subcontractor efforts were directed by E. M. Varholak for Hamilton Standard, and by J. Witzel for Hercules Inc.

This report was submitted in July, 1972.

This technical report has been reviewed and is approved.

K. H. Digges
Kennerly H. Digges
Chief, Mechanical Branch
Vehicle Equipment Division
AF Flight Dynamics Laboratory

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

## LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

LIST OF TABLES

## DEFINITIONS

$e_L$, $e_T$ - Lamina strains parallel and transverse to the fiber direction, respectively (in./in.).

$e_{LT}$ - Laminae shear strain parallel and transverse to the fiber direction (in./in.).

$e_x$, $e_y$ - Laminate strains along the x and y axes of symmetry, respectively (in./in.).

$e_{xy}$ - Laminate shear strain along the axes of symmetry (in./in.).

$E_L$, $E_T$ - Young's modulus of laminae parallel and transverse to the fiber direction, respectively (lb./in.$^2$).

$E_x$, $E_y$ - Young's modulus of laminate along axes of symmetry (lb./in.$^2$).

$f_L$, $f_T$ - Nominal normal stress applied to laminae parallel and transverse to the fiber direction, respectively, (lb./in.$^2$).

$f_{LT}$ - Nominal shear stress applied to laminae parallel and transverse to the fiber direction (lb./in.$^2$).

$f_x$, $f_y$ - Nominal normal stress applied to laminate along the x and y axes of symmetry, respectively (lb./in.$^2$).

$f_{xy}$ - Nominal shear stress applied to laminate along the axes of symmetry (lb./in.$^2$).

$f_{res}$ - Vectorial sum or resultant of the three laminate applied stress components - $f_x$, $f_y$ and $f_{xy}$ (lb./in.$^2$).

$F_L$, $F_T$ - Ultimate allowable normal strengths of a laminae parallel and transverse to the fiber direction, respectively (lb./in.$^2$).

$F_{LT}$ - Ultimate allowable shear strength of a laminae parallel and transverse to the fiber direction (lb./in.$^2$).

| | |
|---|---|
| $F_x$, $F_y$ | Ultimate allowable normal strengths of a laminate along the x and y axes of symmetry, respectively (lb./in.$^2$). |
| $F_{xy}$ | Ultimate allowable shear strength of a laminate along the x and y axes of symmetry, respectively (lb./in.$^2$). |
| $F_{res}$ | Vectorial sum or resultant of the three laminate allowable strengths - $F_x$, $F_y$ and $F_{xy}$ (lb./in.$^2$). |
| V/O | Filament content (% by volume). |
| $\mu_{LT}$/$\mu_{TL}$ | Poisson's ratio for a laminae relating contracting in the T direction due to extension in the L direction and vice versa, respectively. |
| $\mu_{xy}$,$\mu_{yx}$ | Poisson's ratio for a laminate relating contraction in the y direction due to extension in the x direction and vice versa, respectively. |

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## SECTION I

## INTRODUCTION

### 1.1 PROGRAM OBJECTIVE

The aim of this study was to evaluate the advantages of constructing aircraft landing gear assemblies from filament composite materials. The vehicle selected as a basis for this study was the main landing gear for the A-37B aircraft. The existing conventional landing gear assembly for this aircraft is shown in Figures 1-1 through 1-3.

The primary program objective was to design, fabricate and test an assembly from boron filament composites which would duplicate the functional and performance characteristics of the existing A-37B landing gear. The A-37B is a 14000 pounds gross weight aircraft.

### 1.2 PROGRAM APPROACH

Bendix approached the program objective with the following two phase program.

PHASE I

Detailed design and manufacturing trials of the piston, outer cylinder, torque arms, and side brace boron filament components for the A-37B main landing gear. Both epoxy and aluminum matrix materials were evaluated.

PHASE II

Fabrication and test of a boron epoxy A-37B main landing gear assembly.

#### 1.2.1 Phase I

Phase I activity was directed to the following primary goals.

1. Design - Detailed designs were submitted for each of the four primary components: piston-axle, torque arms, outer cylinder-trunnion, and side brace. Concepts were studied for both BORSIC-aluminum and boron-epoxy materials. A complete, functional, landing gear assembly was evolved. Detailed drawings and a parts list for Phase II hardware fabrication were produced.

2. Subscale Testing - Subscale specimens, closely simulating the actual hardware, were fabricated from each of the two materials and structurally tested. The two-fold purpose of this activity was to provide fabrication trials for Phase II hardware and to confirm structural strength procedures used in hardware design. Knowledge gained from these specimens was employed to set up fabrication and processing procedures for the actual landing gear components.

3. Assembly Test Program - A schedule of structural tests to be applied to the full-scale landing gear assemblies was developed.

4. Air Force Review - Phase I results were submitted to the Air Force for its study. The Air Force then selected the components to be pursued further in Phase II. Selection was based on fabrication feasibility, cost, weight and anticipated performance reliability. The Air Force decision was to confine hardware fabrication to epoxy matrix materials with Hercules Inc. as the supplier of the filament composite components.

### 1.2.2 Phase II

Based upon the design selections made by the Air Force at the Phase I review, and at later times in the program, one filament composite landing gear assembly was fabricated. Fabrication tasks involving composite materials were performed by Hercules. Primary metallic hardware was fabricated, and the gear assembled, by Bendix. The landing gear assembly was subjected to a spectrum of structural tests in the Bendix Laboratories.

## 1.3 ASSIGNMENT OF TASKS

This project was conducted by a three-member team consisting of The Bendix Corporation, Energy Controls Division, as the primary contractor, and the Hamilton Standard Division of United Aircraft and Hercules, Inc. as the subcontractors. The essential subcontractor function was to fabricate and supply the filament composite subassemblies for this program. Hamilton Standard dealt with components involving an aluminum matrix and Hercules with those including an epoxy matrix.

The primary functions and assignments may be summarized as follows:

Subcontractors

1. Supplied basic design mechanical properties for composite materials.
2. Provided consultation on the design of composite test specimen and landing gear components.
3. Established processing details for the fabrication of composite parts.
4. Assisted in the analysis of fabrication costs.
5. Fabricated and furnished composite test specimens and landing gear components.
6. Provided consultation on test program.
7. Supplied input for periodic and final reports.

## Bendix

1. Overall program supervision.

2. Design analysis of all structural specimens and hardware.

3. Produced layout, assembly and detailed drawings of all specimens and landing gear components, also parts lists.

4. Procured or fabricated all conventional hardware.

5. Assembled all components into final landing gear assemblies.

6. Defined test programs.

7. Conducted landing gear tests.

8. Writing and publication of periodic and final reports.

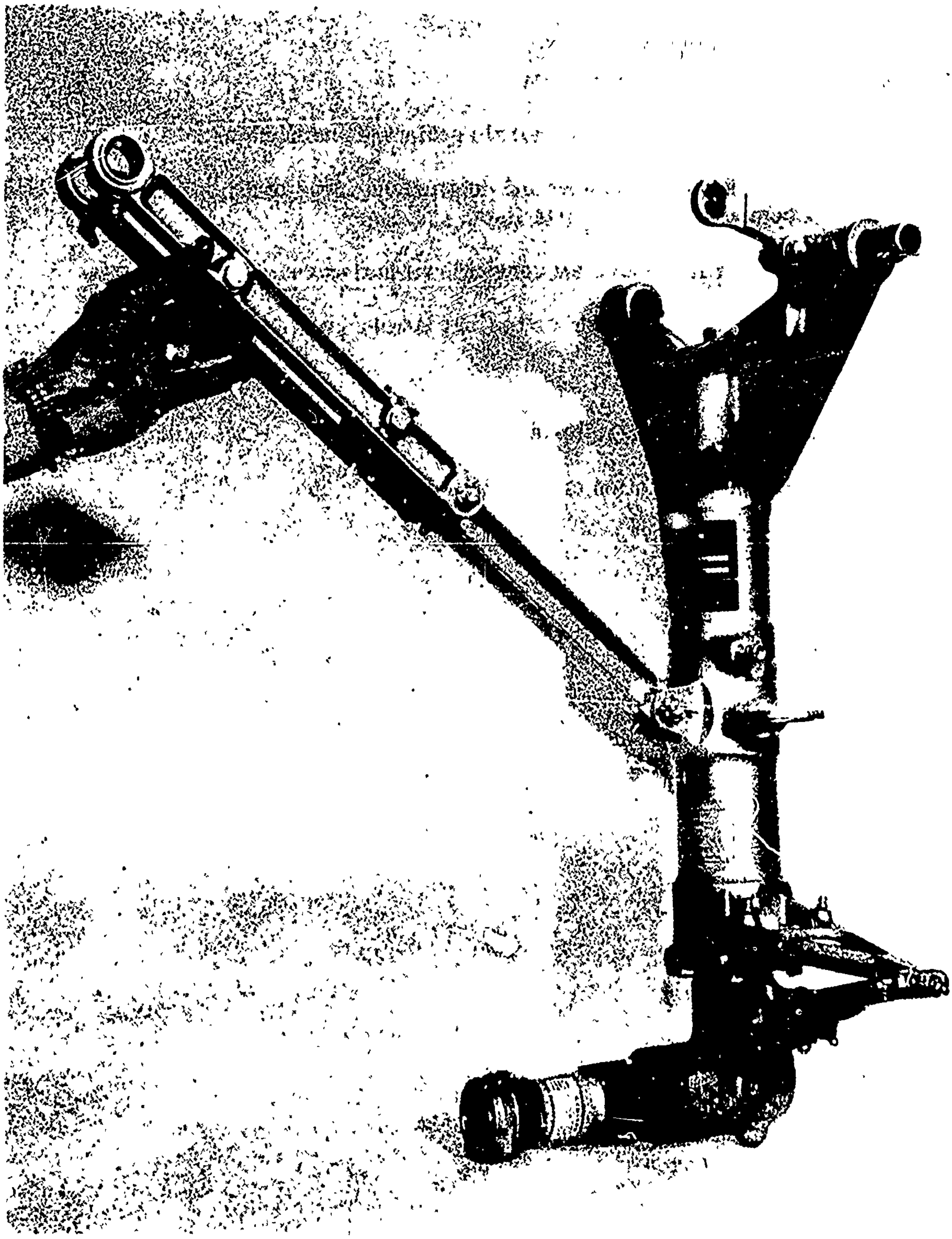


Figure 1-1. Current A-37B Main Landing Gear Assembly

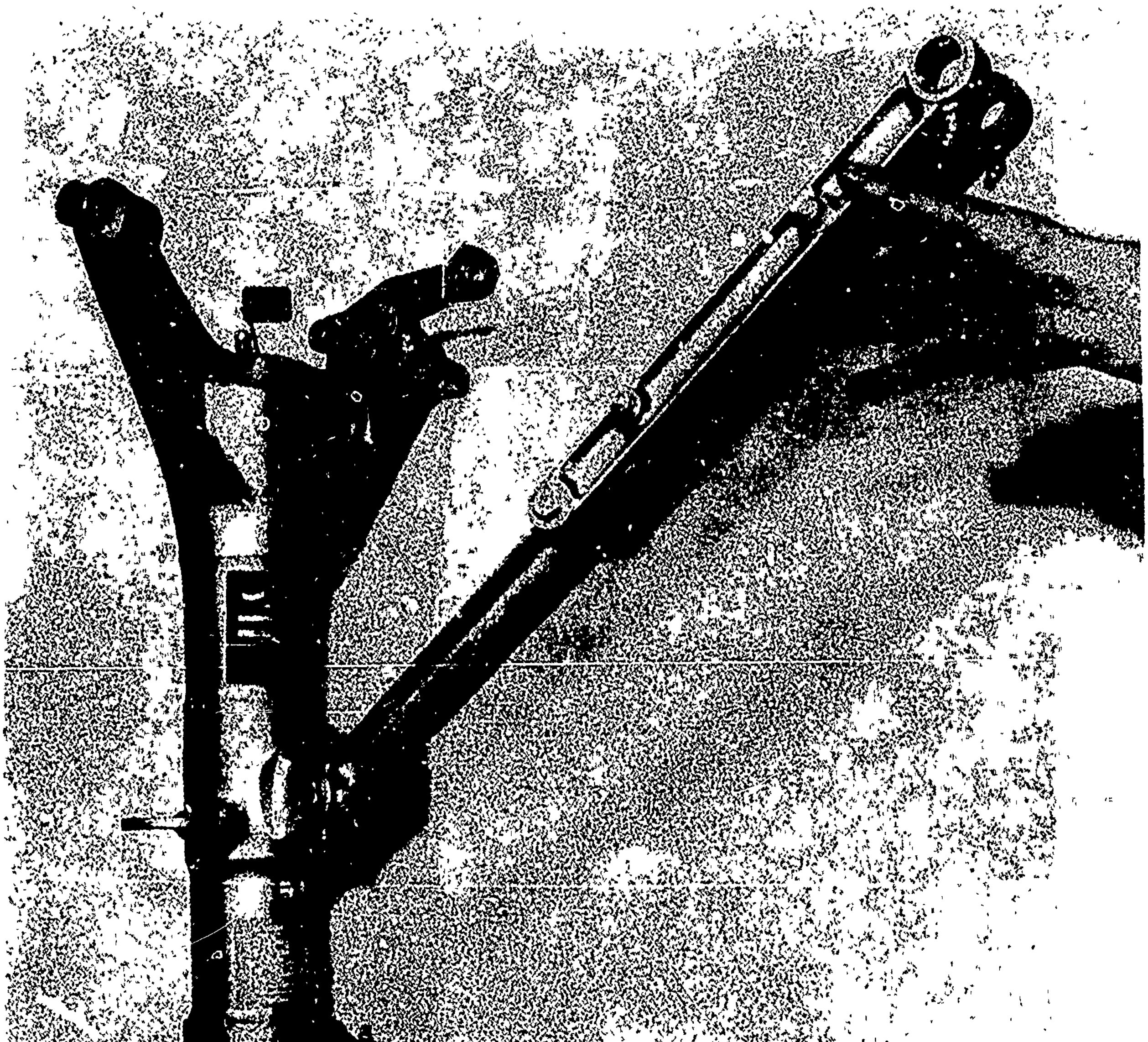


Figure 1-2. Current A-37B Main Landing Gear Assembly

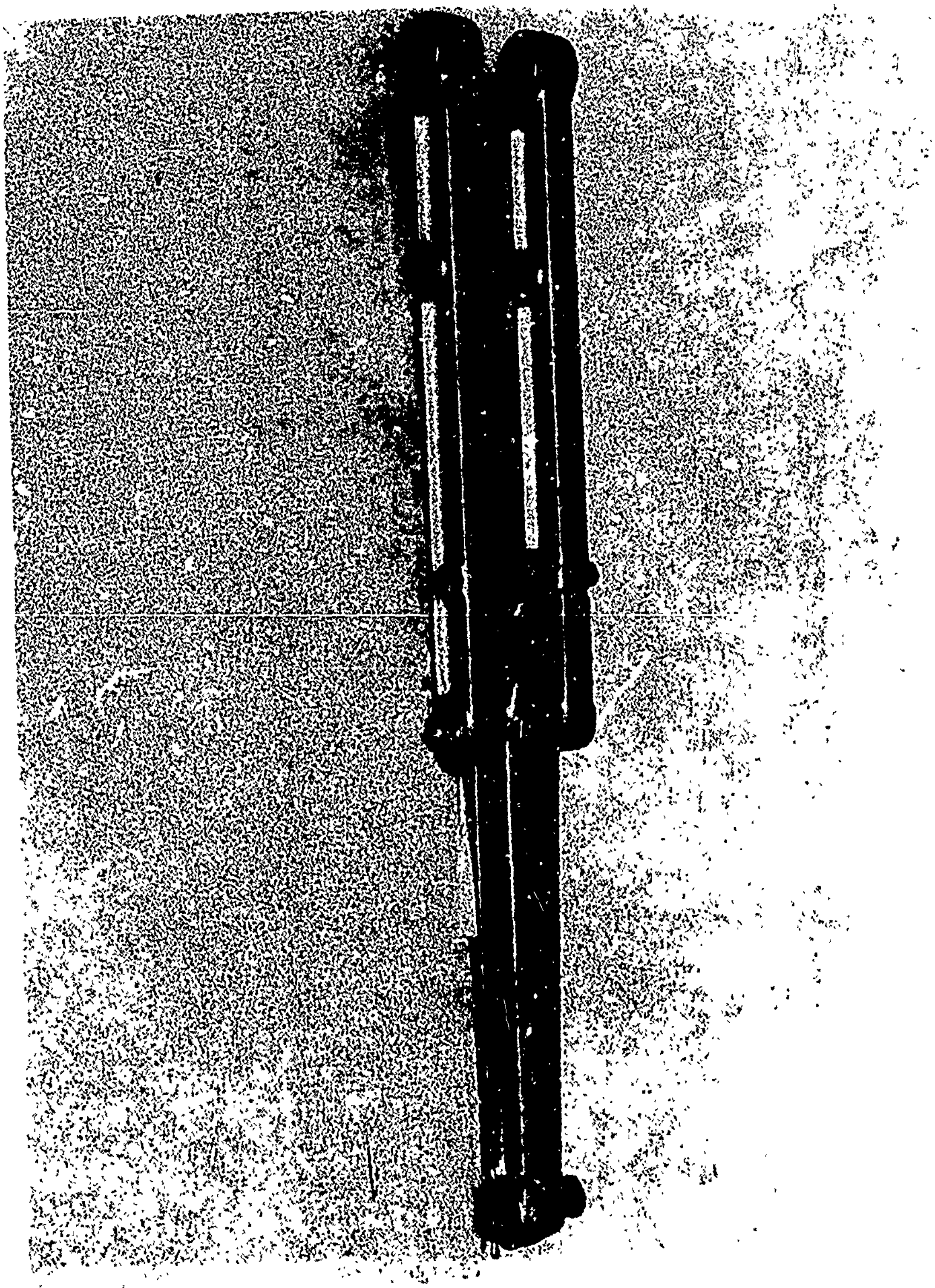


Figure 1-3. Current A-37B Side Brace Assembly

## SECTION II

## SUMMARY

### 2.0 INTRODUCTION

In essence the objective of this program was to design, build, and test one main landing gear assembly for the Cessna A-37B Aircraft from boron composite materials. Four primary structural components were involved: the side brace, the torque arms, the piston, and the outer cylinder. Both boron-epoxy and BORSIC-aluminum composites were considered as candidate materials for each of the components. Phase I included the design activity required to produce fabrication drawings, establish fabrication procedures, and define a test program. Phase II involved the actual fabrication and testing of the landing gear assembly.

This discussion summarizes the results of the program and closes with conclusions and recommendations for further extension of filament composite landing gear technology.

### 2.1 PHASE I - DESIGN

The Phase I activities and results may be summarized as follows.

#### 2.1.1 Review of Filament Composite Technology

A review of the literature and previous work by Bendix, and consultation with the subcontractors and the Air Force were necessary to organize the technology required to successfully complete this program.

These reviews were essential to establish the specific materials to be used, the design allowables for these materials, procedures available for fabricating thick walled products, methods for applying wear and sealing liners to the composite materials, and joint and fittings concepts for high intensity loadings common to landing gear structures.

#### 2.1.2 Structural Design Criteria

1. Landing Gear Design Loads - The design loads and geometry pertaining to the main landing gear of the A-37B aircraft, Reference 12, were obtained from the Air Force at the initiation of the program.

2. Filament Composite Design Data - The mechanical properties required for the structural design of the filament composite components were obtained from material specimen tests performed by the subcontractors during the Phase I period.

### 2.1.3 Landing Gear Design

The work statement specified that the resulting filament composite landing gear design be interchangeable as an assembly with the conventional gear assembly currently installed in the 14000 lb A-37B aircraft. In addition, the new design was to satisfy the same functional requirements as the conventional gear.

1. Structural Design - Strength analysis procedures for basic filament composite members such as cylinders, I-sections, plates, and bars were available from previous programs. However, in this program it was necessary to design load transfer fittings and attachments not previously in existence. The development of some new filament composite structural concepts was therefore necessary. The side brace and fittings, the torque arms, and the socket connections for the outer cylinder-trunnion and the piston-axle joints are in this category. Structural tests of full scale hardware specimens were performed during the design activity to confirm the integrity of these concepts.

2. Fabrication of Hardware Test Specimens - A second purpose for producing the structural hardware specimens was to check out the processing details to be applied to the fabrication of the prototype components during Phase II. These trials pointed up some difficulties in fabricating thick walled cylinders from composite materials. Problems were encountered with both the boron-epoxy and BORSIC-aluminum materials in providing adequate ply compaction and consolidation during fabrication of the tubular products. This problem was particularly prevalent with the BORSIC-aluminum materials.

3. Design of Landing Gear Components - Designs were evolved for the side brace, the torque arms, the outer cylinder, and the piston suitable for fabrication from boron-epoxy materials. Designs also were produced for the side brace and torque arms to be fabricated from the BORSIC-aluminum composite. No designs were completed for the outer cylinder and piston from BORSIC-aluminum composite because of the difficulty in producing adequate cylinders during fabrication of the hardware test specimens.

4. Detailed Drawings and Specifications - Detailed and assembly drawings and the appropriate parts list, as required to fabricate actual hardware were produced. Detailed processing and quality control procedures for producing filament composite parts in Phase II were also established.

### 2.1.4 Weight Analysis

A detailed weights analysis was performed of the filament composite components and assemblies designed for Phase II fabrication. The results indicate potential weight savings which vary from 6 to 33 percent on subassemblies and from 2 to 40 percent on specific components depending on which materials are used. These savings were realized from designs which were not optimized, but were constrained by a simple material substitution with geometry and envelope fairly fixed. It is believed that greater savings could be available in new aircraft situations where structural geometry and envelope requirements are more flexible.

### 2.1.5 Test Specifications

A test program for the filament composite gear assembly was detailed. The specification included leakage and proof pressure tests, an experimental stress survey, and structural strength tests.

## 2.2 PHASE I - REVIEW

The results of the Phase I work were presented by Bendix and its subcontractors to the Air Force during a program review meeting. After evaluating the data presented, the Air Force authorized the building and testing of a landing gear assembly comprising a piston, outer cylinder, and side brace fabricated from boron-epoxy composites and the conventional steel torque arms currently furnished for the conventional A-37B main landing gear.

## 2.3 PHASE II - FABRICATION AND TESTING

The work during this period was concentrated on fabricating and testing the specific boron-epoxy prototype assembly selected during the Phase I Air Force review.

### 2.3.1 Fabrication

Fabrication tasks comprised two separate groups -- those performed by Hercules, Inc. and those carried out by Bendix.

Hercules Activity - The primary function of this contractor was to fabricate the basic boron-epoxy components. Fabrication of the side brace components resulted in composite products of excellent quality with good overall dimensional control. However, some problems still persisted with ply consolidation in the fabrication of the thick walled outer cylinder and piston tubes.

Bendix Activity - All conventional metallic hardware and fittings were procured or manufactured by Bendix. In addition, finishing operations were applied to the filament composite products furnished by Hercules, Inc. This included grinding and machining to final dimensions, application of wound glass filament reinforcements, and the attachment of metallic fittings. Finally, all components were fitted into one landing gear assembly.

Nickel Liners - Nickel liners were applied to the outer cylinder and piston tubes in accordance with processing procedures previously developed during Air Force sponsored studies. Two fundamentally different problems were encountered in the application of the liners -- one associated with the outer (OD) liner and one with the inner (ID) liner. For the inner surface a good quality liner was achieved but adhesion to the composite cylinder was poor. In the case of the outer surface, adhesion appeared good but cracking of the liner was experienced during deposition and final machining.

### 2.3.2 Testing

Three primary types of tests were applied to the composite landing gear assembly: leakage and proof pressure tests, experimental stress survey, and ground loads structural strength tests.

2.3.2.1 Pressure Tests

Hydraulic pressure testing of the shock absorber assembly was performed in accordance with aircraft shock absorber specification MIL-L-8552C. The piston was installed in this assembly without an inner nickel liner because of lack of adhesion of the liner to the composite tube. The assembly was subjected to internal pressures varying from 90 to 2650 psi for a total period of 40 hours without any apparent structural or leakage difficulties.

2.3.2.2 Experimental Stress Analysis

A stress analysis using rosette strain gages applied to the filament composite components was performed. Good agreement was achieved between measured and calculated results.

2.3.2.3 Structural Strength Tests

The landing gear assembly was subjected to three different design critical ground loads. Loading was applied alternately among the three loading conditions and increased in increments to the design magnitudes. The structure sustained 31 separate loadings ranging in magnitude from 25 to 150 percent of design limit level.

A number of local attachment problems were experienced during loading. It was possible to repair these and continue the loading.

Primary structural performance and load levels achieved may be summarized as follows:

Side Brace -

1. A tension load level of 100 percent of design limit was achieved with no apparent damage to the brace.

2. The compression load strength for the assembly was restricted to 98 percent of design limit load by crushing of the inner edge of the filament composite flanges in the upper links at a location immediately adjacent to the center hinge pin fitting. Overloading of one edge of the composite flanges was attributed to excessive flexibility of the steel hinge pin which permitted eccentric loading of the column flanges.

3. In a separate test the lower link supported a compression load of 115 percent of design limit, when a shear out of the aluminum end fitting was experienced.

4. In summary, the strength of the side brace was limited by the strength of the metallic fittings. No structural problems were attributable directly to the filament composite components.

Piston -

A design limit load level of 112 percent was reached when rupture of the piston was sustained at the location coinciding with the lower piston bearing. An attempt to determine if this was a design associated problem was negated by the existence of a rather severe delamination in the tube as fabricated.

A positive aspect of the piston design is that the piston-axle joint was capable of supporting this load level without difficulty.

Outer Cylinder -

1. A load level of 88 percent of design limit was reached when a separation occurred between the glass-epoxy overwrap and the boron-epoxy tube at the side brace attachment.

2. Rupture of the outer cylinder was sustained at 120 percent of design limit load. The rupture occurred at the juncture of the boron-epoxy cylinder with the trunnion fitting. As with the piston tube, an attempt to evaluate the design aspects of the strength of this joint was complicated by ply separations contained in the boron-epoxy cylinder.

Test Summary

The entire structural test performance is summarized in some detail in Section VII, Tables 7-2 and 7-3.

## 2.4 CONCLUSIONS AND RECOMMENDATIONS

The statement of work which this contractor followed states that the objective of the program is to fabricate a prototype composite aircraft landing gear in accordance with the A37-B requirements and determine through testing the extent to which boron composite materials can be utilized in aircraft landing gear applications. The results of the program indicate that landing gear assemblies may be constructed from filament composite materials which result in weight savings and are structurally reliable.

This was the first known attempt to design and produce a fully functional filament composite landing gear assembly. An assembly was produced which sustained slightly more than limit design loads.

In general, further work in the following areas is required to achieve completely satisfactory results in future applications of boron-epoxy to landing gear:

1. Fabrication of thick walled products.

2. The development of suitable liners and coatings for hydraulic cylinders.

3. The analysis and design of attachments and joints.

Some detailed recommendations in these areas based on this contractor's experience with the A37-B gear are given in Paragraph 7.3 of this report.

## SECTION III

## TECHNOLOGY REVIEW

### 3.0 INTRODUCTION

The contract work statement indicated that the required design and fabrication technology was available for initiating and carrying out this project. Special emphasis was placed on five programs conducted by Bendix and McDonnell Douglas and designated by the Air Force as being directly applicable to landing gear components, References (1) through (5). Of particular interest was the work described in Reference (5) which deals with test work being carried out by the Air Force in connection with wear and sealing liners for filament composite cylinder surfaces. A continuous review of new material from the literature was carried on during the conduct of the study to complete the required technology. This review pointed up the existence of certain complexities in this program which had not been dealt with previously. The following paragraphs summarize the technology available at the initiation of the study and how it compared to the technical requirements of the program. In addition, where information gaps existed the action taken to create the necessary information is described.

### 3.1 BORON-EPOXY COMPOSITE

#### 3.1.1 Selection of a Resin System

The final selection of a resin system for this program was made by comparing the performance of three systems BP-907, Narmco 5505, and SP-272. At the time the selection was made all three systems were being used with boron filaments in a number of active programs. These applications are summarized in Table 3-1. As may be noted Hercules had achieved experience with both the BP-907 and 5505 systems. Ease of manufacture and cylinder quality were found to be much greater with the BP-907 system. As a result of these two programs, Hercules strongly favored the use of BP-907 systems in the A-37B landing gear program.

The selection of the system could not be based on ease of manufacturing alone, but also on comparative strength data. Pertinent information was collected from the sources cited in Table 3-1. This information is summarized for each system in Tables 3-2, 3-3 and 3-4. A direct comparison of the performance of the three boron-epoxy combinations is given in Table 3-5 in terms of the six primary mechanical properties. A comparison of these properties, and the others, revealed the BP-907 system to be essentially equivalent to the other two systems.

Consequently, based upon experience and ease of fabrication, coupled with good mechanical performance, the BP-907 system was selected for this program.

### 3.1.2 Areas for Further Study

Development work on boron-epoxy structures has been in progress for some years. However, as of the date of initiation of this contract, the emphasis had been placed on thin shell or skin type structures. Much of the available technology was not transferable to primary type structures which are subjected to high load intensities. Following are some of the areas where some minimum development work was at least necessary in order to accomplish the goals of this project.

1. A surface liner is required on the surfaces of the outer cylinder and piston to resist leakage and bearing wear. At the initiation of this contract liner development was only in an early stage of development. Concurrent with the conduct of this design study the Air Force continued work on the development of a metal liner. The characteristics of the resulting liner are discussed in Paragraph 5.3.1.5.

2. Improved fabrication procedures were required for thick-walled, crossply, boron-epoxy cylinders. Pilot runs were made on trial specimens for the purpose of improving fabrication techniques and product quality.

3. Adequate design data and fabrication procedures for affixing metal fittings to boron-epoxy cylinders were not available from the literature. The structural integrity of the outer cylinder and the piston are highly dependent on this aspect of design. Detailed design and analysis were necessary to arrive at adequate attachment concepts.

4. Design data for boron-epoxy pinned joints was not available for the load intensities and lug configurations encountered in various landing gear connections. It was necessary to test a number of pin bearing specimens to obtain the required data.

5. Satisfactory procedures for designing and constructing high strength complex structural configurations such as the trunnion and other fittings (reference Figures 5-85, -86, -89 and -94) from boron-epoxy composites were not available at the initiation of this contract. This technology gap remains unfilled.

## 3.2 BORON-ALUMINUM COMPOSITE

Landing gear construction is typified by highly loaded mechanical joints which present a primary design challenge because the weight penalties inherent within the joint often tend to erase the weight savings derived within the main body of the structure. The low strengths available with epoxy adhesives are not suitable for efficient bonded joint design. A metal matrix construction becomes attractive for landing gear construction because of the high bonding strengths available with the brazing process.

The BORSIC-aluminum composite was selected as a candidate material for construction of the A-37B landing gear because of this potential for providing the best choice in complex structural configurations. However, as with the boron-epoxy composite, some details concerning mechanical properties and fabrication processes were not available at the initiation of this study. This is an understandable aspect considering the relatively

recent origin of the metal matrix composites and their still propietary nature. Following are some areas where some further investigations were necessary to provide adequate design and fabrication procedures.

1. The effects of brazing temperature on the strength of BORSIC-aluminum composites were unknown. This information was obtained by fabricating and testing the tensile specimens described in Appendix A.

2. More information was necessary on the strength of attachment joints bonded by the brazing method.

3. Design data for boron-epoxy pinned joints was not available for the load intensities and lug configurations encountered in various landing gear connections. It was necessary to test a number of pin bearing specimens to obtain the required data.

4. Techniques were necessary for fabricating crossply cylinders. The fabrication trials described in Paragraph 8.1.5 were conducted for this purpose.

5. Satisfactory procedures for designing and constructing high strength complex structural configurations such as the trunnion and other fittings (reference Figure 5-34) from BORSIC-aluminum composites were not available for purposes of this contract. As with the boron-epoxy composite this gap still exists.

TABLE 3-1. SUMMARY OF RESIN USERS

| Resin System | User | Application | Test Data | Source Reference |
|---|---|---|---|---|
| BP-907 | Vertol | Helicopter blades | Table 3-2 | 8, 9, 7 |
| | Hercules | Vertol helicopter blades<br>Grumman LEM struts | | |
| 5505 | General Dynamics | Horizontal stabilizer | Table 3-3 | |
| | Grumman | Wing structure | | 6 |
| | Hercules | Grumman LEM struts | | 9,11 |
| SP-272 | Lockheed | C-5A leading edge | Table 3-4 | 6 |
| | Vertol | Helicopter blades | | 10 |

TABLE 3-2. BORON/BP-907-104A MECHANICAL PROPERTIES (ULTIMATE)

| Property | Type of Test | Temp. (°F) | Boron* Filament Volume (%) | No. Plies/ Thickness | Average Value |
|---|---|---|---|---|---|
| $E_L$ (psi x $10^{-6}$) | 0° tensile | 77 | 53.5 | 6/.031 | 32.2 |
| $F_L$ (ksi) | 0° tensile | 77 | 53.5 | 6/.031 | 207.9 |
| $e_L$ (in./in. x $10^3$) | 0° tensile | 77 | 53.5 | 6/.031 | 6.0 |
| $\mu_{LT}$ | 0° tensile | 77 | 53.5 | 6/.031 | .142 |
| $E_T$ (psi x $10^{-6}$) | 90° tensile | 77 | 55.3 | 6/.030 | 3.4 |
| $F_T$ (ksi) | 90° tensile | 77 | 55.3 | 6/.030 | 12.8 |
| $e_T$ (in./in. x $10^3$) | 90° tensile | 77 | 55.3 | 6/.030 | 6.33 |
| $F_{LT}$ (ksi) | ILS | 77 | 59.2 | 24/.112 | 12.1** |
| $E_X$ (psi x $10^{-6}$) | ± 45° tensile | 77 | 53.5 | 6/.031 | 2.82 |
| $F_X$ (ksi) | ± 45° tensile | 77 | 53.5 | 6/.031 | 22.7 |
| $F_L$ (psi x $10^{-6}$) | 0° flexure | 77 | 55.3 | 16/.080 | 295.1 |
| $E_L$ (psi x $10^{-6}$) | 0° flexure | 77 | 55.3 | 16/.080 | 32.4 |

* *Calculated* based upon 220 fibers/inch, 0.004 inch fiber diameter.
** Short beam shear 5/1 span to depth.

TABLE 3-3. NARMCO 5505 BORON-EPOXY MECHANICAL PROPERTIES (ULTIMATE)

| Property | Type of Test | Temp. (°F) | Boron Filament Volume (%) | Average Value |
|---|---|---|---|---|
| $E_L$ (psi x $10^{-6}$) | 0° tensile | 75 | 51 | 30.9 |
| $F_L$ (ksi) | 0° tensile | 75 | 51 | 208.3 |
| $e_L$ (in./in. x $10^3$) | 0° tensile | 75 | 51 | 6.93 |
| $\mu_{LT}$ | 0° tensile | 75 | 51 | .28 |
| $E_T$ (psi x $10^{-6}$) | 90° tensile | 75 | 51 | 2.5 |
| $F_T$ (ksi) | 90° tensile | 75 | 51 | 8.68 |
| $e_T$ (in./in. x $10^3$) | 90° tensile | 75 | 51 | 3.71 |
| $F_{TL}$ (ksi) | ILS | 75 | 51 | 5.16* |
| $E_X$ (psi x $10^{-6}$) | ± 45° tensile | 75 | 51 | 3.0 |
| $F_X$ (ksi) | ± 45° tensile | 75 | 51 | 17.8 |
| $E_L$ (psi x $10^{-6}$) | 0° flexure | 75 | 51 | 28.5 |
| $F_L$ (psi x $10^{-6}$) | 0° flexure | 75 | 51 | 247.0 |
| $E_L$ (psi x $10^{-6}$) | 0° compression | 75 | 51 | 34.8 |
| $F_L$ (ksi) | 0° compression | 75 | 51 | 378.0 |

* Notched tensile shear.

TABLE 3-4. 3M SP-272 BORON–EPOXY MECHANICAL PROPERTIES (ULTIMATE)

| Property | | Type of Test | Temp. (°F) | Boron Filament Volume (%) | Average Value |
|---|---|---|---|---|---|
| $E_L$ | (psi x $10^{-6}$) | 0° tensile | 75 | 51 | 29.6 |
| $F_L$ | (ksi) | 0° tensile | 75 | 51 | 185.9 |
| $e_L$ | (in./in. x $10^3$) | 0° tensile | 75 | 51 | 6.26 |
| $\mu_{LT}$ | | 0° tensile | 75 | 51 | .234 |
| $E_T$ | (psi x $10^{-6}$) | 90° tensile | 75 | 51 | 2.8 |
| $F_T$ | (ksi) | 90° tensile | 75 | 51 | 11.7 |
| $e_T$ | (in./in. x $10^3$) | 90° tensile | 75 | 51 | 4.87 |
| $F_{TL}$ | (ksi) | ILS | 75 | 51 | 8.0* |
| $E_X$ | (psi x $10^{-6}$) | ± 45° tensile | 75 | 51 | 3.1 |
| $F_X$ | (ksi) | ± 45° tensile | 75 | 51 | 22.2 |
| $E_L$ | (psi x $10^{-6}$) | 0° flexure | 75 | 51 | 29.5 |
| $F_L$ | (psi x $10^{-6}$) | 0° flexure | 75 | 51 | 256.6 |
| $E_L$ | (psi x $10^{-6}$) | 0° compression | 75 | 51 | 35.6 |
| $F_L$ | (ksi) | 0° compression | 75 | 51 | 443.5 |

* Notched tensile shear.

TABLE 3-5. COMPARISON OF PRIMARY RESIN PERFORMANCE

| Property | BP-907 | 5505 | SP-272 |
|---|---|---|---|
| $E_L$, psi x $10^{-6}$ | 32.2 | 30.9 | 29.6 |
| $F_L$, ksi | 207.9 | 208.3 | 185.9 |
| $e_L$, in./in. x $10^3$ | 6.0 | 6.93 | 6.26 |
| $E_T$, psi x $10^{-6}$ | 3.4 | 2.50 | 2.80 |
| $F_T$, ksi | 12.8 | 8.68 | 11.70 |
| $e_T$, in./in. x $10^3$ | 6.33 | 3.71 | 4.87 |
| Filament Vol., % | 53.5 (L)<br>55.3 (T) | 51 | 51 |

## SECTION IV

## STRUCTURAL DESIGN CRITERIA

### 4.0 INTRODUCTION

The structural design of the composite landing gear assembly was governed by the following requirements.

a. Landing gear design loads.

b. Materials design properties.

c. The philosophy concerning factors and margins of safety.

### 4.1 DESIGN LOADS

The ground loads specified for the design of the composite gear were given in Reference 12.

The application of these loads to filament composite components resulted in an increase in piston and outer cylinder outside diameters. Consequently it was necessary to modify the basic landing gear geometry in order to retain adequate mechanical clearance between the various components of the gear assembly. The revised geometry is shown in Figure 4-1.

The combination of the modified geometry and the ground loads of Reference 12 results in the individual component loadings summarized in Figure 4-2 and Tables 4-1 and 4-2. All loads were taken as ultimate loads, i.e., limit or landing design loads multiplied by a safety factor of 1.5. The philosophy behind this practice is explained in Paragraph 4.5.

### 4.2 MATERIALS DESIGN PROPERTIES

The basic mechanical properties used in the design of filament composite members for this investigation are shown in Table 4-3. These properties were supplied by Hamilton Standard and Hercules for their respective materials. The source for the BORSIC-aluminum data is Reference 13. The derivation of the boron-epoxy data is explained in Appendix B.

It is to be noted that some values in Table 4-3 for BORSIC-aluminum composite must be adjusted for variation due to time at brazing temperature in accordance with the curve of Figure 4-3. The derivation of this curve is explained in Appendix A.

For the design of conventional metal parts, the design values of MIL-HDBK-5A (Reference 16) were prescribed.

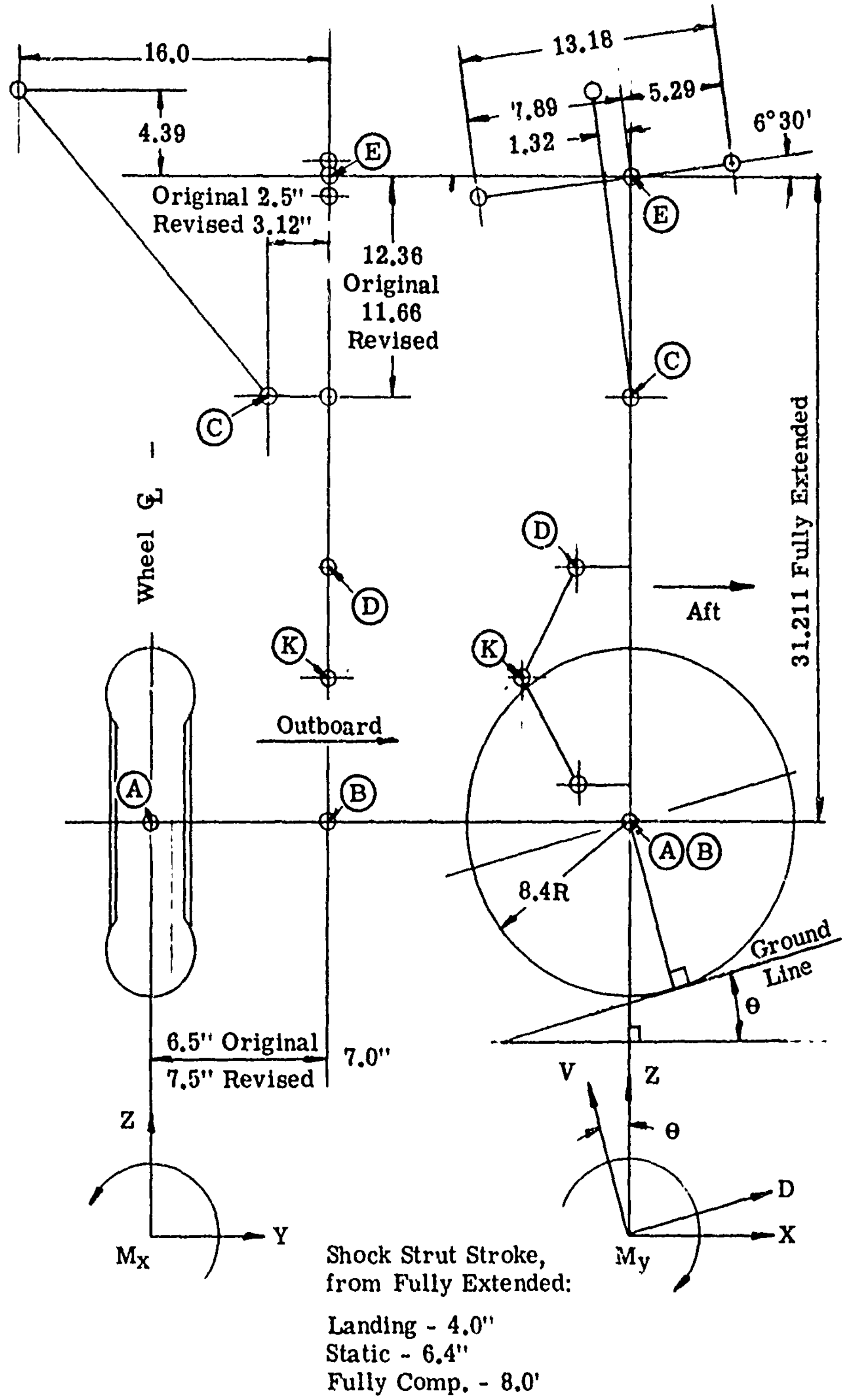



Figure 4-1. Geometry-Left Hand Gear

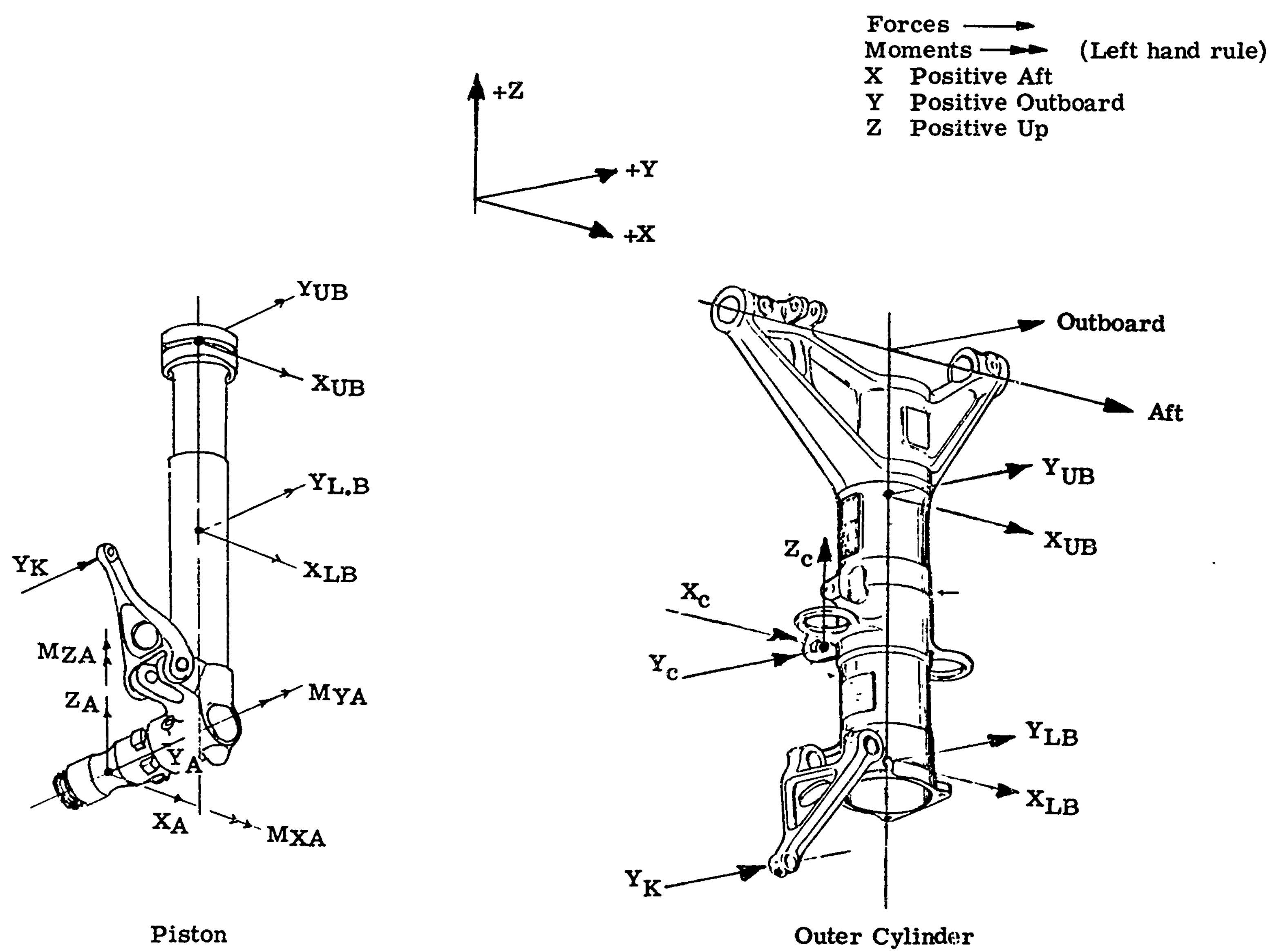



Figure 4-2. Free Body Diagrams

TABLE 4-1. ULTIMATE LOADS APPLIED TO PISTON, OUTER CYLINDER, AND TORQUE ARM ASSEMBLIES

| PISTON | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Load Condition | | | $Z_A$ | $X_A$ | $Y_A$ | $M_{ZA}$ | $M_{XA}$ | $M_{YA}$ | $X_{LB}$ | $Y_{L.B}$ | $Y_K$ | $X_{UB}$ | $Y_{UB}$ |
| 2 Pt. Level Landing | Max. Vert. | 1A | 15000 | -5600 | 0 | 0 | 0 | 0 | 9500 | 15300 | -5200 | -3900 | -10100 |
| | Spin-up | 1B | 7700 | 7300 | 0 | 0 | 0 | 0 | -12100 | -3900 | 6800 | 4800 | -2900 |
| | Spring Back | 1C | 11700 | -9700 | 0 | 0 | 0 | 0 | 16200 | 18200 | -9100 | -6400 | -9100 |
| Tail Down Landing | Max. Vert. | 2A | 13900 | -9600 | 0 | 0 | 0 | 0 | 16000 | 19400 | -9000 | -6400 | -10400 |
| | Spring Back | 2C | 8300 | -10400 | 0 | 0 | 0 | 0 | 14900 | 17000 | -9700 | -4500 | -7200 |
| Drift Landing | Right | 3A | 7700 | -900 | 4700 | 4400 | 38800 | 0 | 1400 | -6100 | -300 | -500 | 1800 |
| | Left | 3B | 7700 | -900 | -6200 | -5900 | -51700 | 0 | 1400 | 21000 | -1600 | -500 | -13300 |
| Braked Roll | | 4A | 11400 | 7200 | 0 | 0 | 0 | -70600 | -14700 | -1300 | 6100 | 7500 | -4800 |
| Reverse Brake | | 5A | 9500 | -9500 | 0 | 0 | 0 | 70600 | 17900 | 14000 | -8200 | -8300 | -5800 |
| Right Turn | | 6A | 11500 | -1300 | -5800 | -5500 | -48000 | 0 | 1800 | 19100 | -1700 | -500 | -11600 |
| 3G Taxi | | 7 | 19200 | | | | | | | | | | |

| OUTER CYLINDER | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Load Condition | | | $X_{LB}$ | $Y_{LB}$ | $Y_K$ | $X_C$ | $Z_C$ | $Y_C$ | $X_{U.B}$ | $Y_{U.B}$ |
| 2 Pt. Level Landing | Max. Vert. | 1A | -9500 | -15300 | 5200 | 1100 | -9300 | 7500 | 3900 | 10100 |
| | Spin-up | 1B | 12100 | 3900 | -6800 | 500 | -4100 | 3300 | -4800 | 2900 |
| | Spring Back | 1C | -16200 | -18200 | 9100 | 900 | -7600 | 6200 | 6400 | 9100 |
| Tail Down Landing | Max. Vert. | 2A | -16000 | -19400 | 9000 | 1000 | -8900 | -7230 | 6400 | 10400 |
| | Spring Back | 2C | -14900 | -17000 | 9700 | 600 | -5600 | 4600 | 4500 | 7200 |
| Drift Landing | Right | 3A | -1400 | 6100 | 300 | -1000 | 9000 | -7300 | 500 | -1800 |
| | Left | 3B | -1400 | -21000 | 1600 | 2600 | -22600 | 18300 | 500 | 13300 |
| Braked Roll | | 4A | 14700 | 1300 | -6100 | 700 | -6300 | 5100 | -7500 | 4800 |
| Reverse Brake | | 5A | -17900 | -14000 | 8200 | 700 | -6300 | 5100 | 8300 | 5800 |
| Right Turn | | 6A | -1800 | -19100 | 1700 | 2600 | -22700 | 18400 | 500 | 11600 |

NOTE: Loads in pounds.

TABLE 4-2. SIDE BRACE LOADS - ULTIMATE

| Load Condition | | | Brace Load, Pounds |
|---|---|---|---|
| 2 Pt. Level Landing | Max. Vert. | 1A | -10,400 |
| | Spin Up | 1B | -4,600 |
| | Spring Back | 1C | -8,500 |
| Tail Down Landing | Max. Vert. | 2A | -10,000 |
| | Spring Back | 2C | -6,300 |
| Drift Landing | Right | 3A | +13,800 |
| | Left | 3B | -29,800 |
| Braked Roll | | 4A | -7,000 |
| Reverse Brake | | 5A | -7,000 |
| Right Turn | | 6A | -29,600 |

NOTE:
(+) tension, (-) compression

TABLE 4-3. ULTIMATE DESIGN PROPERTIES FOR UNIDIRECTIONAL PLY

| | BORSIC-aluminum | Boron-epoxy |
|---|---|---|
| $F_L(t)$, psi | *140,000 | 212,200 |
| $F_L(c)$, psi | *248,000 | 338,600 |
| $F_T(t)$, psi | 13,000 | 13,000 |
| $F_T(c)$, psi | 18,000 | 17,100 |
| $F_{LT}$, psi | 14,000 | 18,200 |
| $E_L$, psi | $30 \times 10^6$ | $30.3 \times 10^6$ |
| $E_T$, psi | $12 \times 10^6$ | $3.1 \times 10^6$ |
| $G_{LT}$, | $6 \times 10^6$ | $0.8 \times 10^6$ |
| $\mu_{LT}$ | 0.22 | 0.16 |
| $\mu_{TL}$ | 0.09 | 0.016 |

*These values to be adjusted per Figure 4-3.
Above data for 50 percent fiber volume.
(t) indicates tension (c) indicates compression

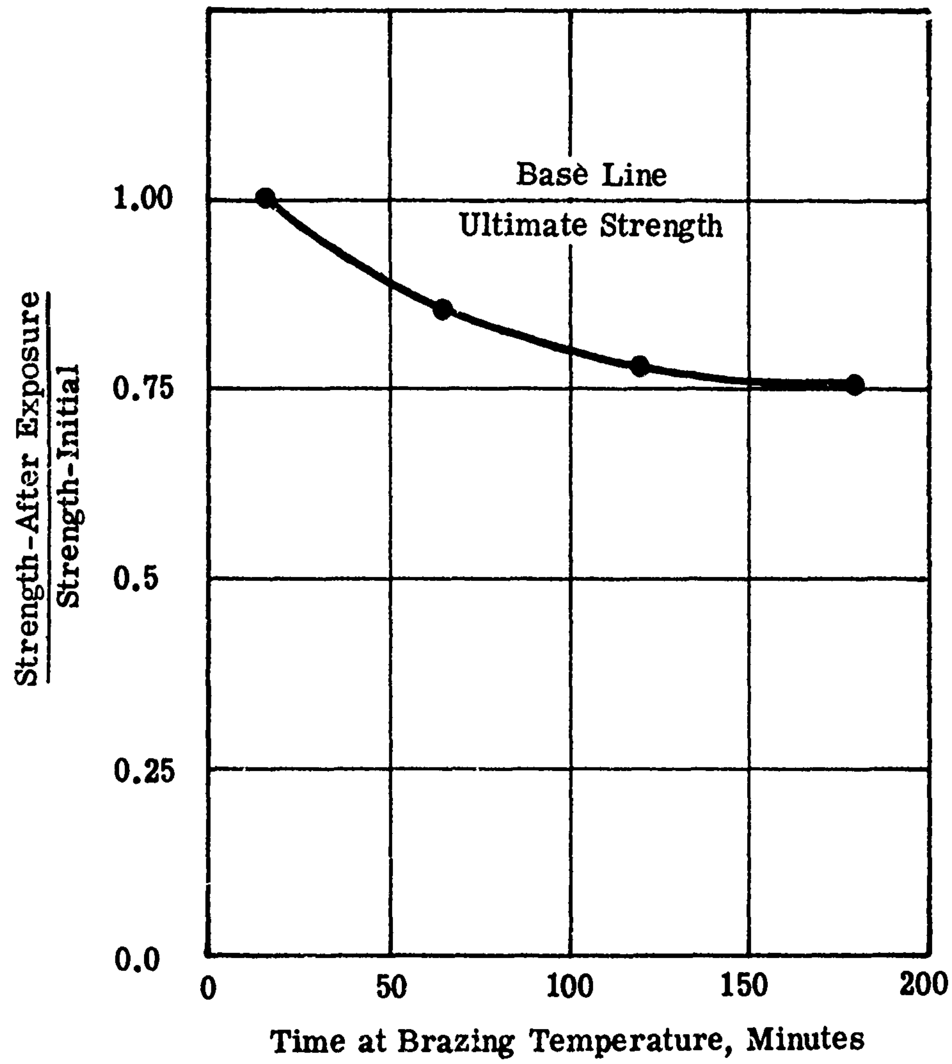



Figure 4-3. Variation in Strength of BORSIC-Aluminum Composite with Exposure to Temperature

## 4.3 LAMINATE DESIGN CRITERIA

### 4.3.1 Computer Program for Laminate Strength

The allowable stresses for laminates were generated by the Bendix laminate characterization computer program 257. The underlying laminate theory is similar to that described in Reference 14.

The characterization process starts with the individual lamina, or ply, as the basic structural element of the laminate, Table 4-3. The characterization program first uses the ply elastic properties and the ply orientations in the standard transformation and integration process to determine the elastic properties of the laminate. The elastic properties of the laminate are used to calculate the laminate strains resulting from a given biaxial state of stress. The laminate strains are transformed to give the state of strain along the axes of symmetry of each ply which are then used to calculate the corresponding state of stress in each ply. The imminence of failure in each ply is evaluated by Hill's failure criteria. The state of stress applied to the laminate is incremented until failure is indicated by Hill's criteria in one or more of the individual plys. Each ply failure is then investigated to determine if the damage has occurred in the matrix or in the fibers. The elastic properties of a failed ply are modified to reflect the fiber or matrix damage, and the laminate stiffness and compliance matrices are recalculated. The next increment of stress is applied and the process is repeated until the laminate is considered to be failed.

Laminate failure criteria is as follows. Matrix failure usually occurs at different stress levels than initial fiber failure and initial ply failure often occurs at lower stress levels than total laminate failure. In the absence of experimental data for the laminate, the investigator must choose one of these stress levels as the design allowable. In the Bendix design work for this program, the laminate is considered to be failed when the fiber ultimate stress has been exceeded in more than one ply orientation.

The adequacy of the above approach for computing laminate strength has been confirmed by comparing predictions with test results carried out earlier by Bendix (Reference 1) and also test results from this current program (Section 5.0). Further confirmation was obtained by comparing predictions with the results of the biaxial stress test work carried out by Grumman (Reference 15).

The state of stress at failure constitutes a point on the laminate failure surface. For a design problem, the failure level is determined for several states of stress and then plotted to form a laminate failure surface. Examples of these plots are shown in Appendices E, F, and G.

### 4.3.2 Margins of Safety

The laminate design approach employed by Bendix is to calculate the nominal applied stresses at a particular point of the structure and compare them to the nominal allowable stresses for the particular laminate pattern at that location. For the two-dimensional case, the state of stress is expressed in terms of the stress components oriented with the laminate axes of symmetry. These stress components are denoted as $f_x$, $f_y$ and $f_{xy}$. The corresponding allowable membrane stresses are denoted as $F_x$, $F_y$ and $F_{xy}$.

The adequacy of the trial design is evaluated by comparing the resultant, or vectoral, sum of the working stress components to the resultant of the allowable stress components for the same stress ratios, so that

$$f_{res} = f_x \mathrel{+\!\!\!\rightarrow} f_y \mathrel{+\!\!\!\rightarrow} f_{xy}$$

$$F_{res} = F_x \mathrel{+\!\!\!\rightarrow} F_y \mathrel{+\!\!\!\rightarrow} F_{xy}$$

where

$$F_y/F_x = f_y/f_x$$

$$F_{xy}/F_x = f_{xy}/f_x$$

The margin of safety is given by the expression

$$M.S. = F_{res}/f_{res} - 1.0$$

## 4.4 STRENGTH OF JOINTS

As indicated in Paragraph 3.0 it was necessary during this program to obtain experimentally some joint strength data not previously available from other sources.

### 4.4.1 Pin Bearing Strength

Pinned joints were used in a number of structural configurations considered during this program. The tear-out strengths of such joints are given in Table 4-4. Fabrication and test data pertaining to the joint specimens from which these strength data were obtained are given in Paragraphs 8.1.2 and 8.2.2 and Appendices C and D, respectively.

### 4.4.2 Bond Strength

Bonded joint strength was required for both epoxy adhesive and aluminum brazed joints. The allowable ultimate shear strength used in the design of bonded joints was taken as

Adhesive Joints - 3360 psi
Brazed Joints - 10000 psi

For the adhesive joints, this value represents magnitudes attained during specimen tests performed as part of this study. These tests are described in Paragraph 5.3.1.3 (see summary for forty-eight and thirty-two ply specimens) and also in Paragraph 8.2.5.1 (see section dealing with ten-ply cylinder).

The allowables selected for aluminum brazed joints are based on starting with $F_{LT}$ = 14000 psi from Table 4-3 as the maximum possible shear strength. Studies of Reference 4 test data on joints indicates a 1.4 stress concentration factor as typical for scarfed joints. This leads to a nominal design value of 10000 psi. Where a particular configuration indicates a higher concentration factor, the design value was reduced accordingly.

The shear strength values for joints will vary from joint to joint depending on the specific joint configuration and the associated stress concentrations. However, the above values were taken from representative configurations, and are believed to be conservative since, in most cases, the actual performance was better than the design values shown above. In addition, these values agree in general with those given in the literature for similar configurations.

## 4.5 STRUCTURAL DESIGN PHILOSOPHY

### 4.5.1 Factor of Safety

The contract work statement required that the composite gear assembly be designed to the same structural strength criteria used by Cessna for the existing conventional landing gear (Reference 12). The existing assembly was designed according to the MIL-A-8860 series of Specifications (References 17 and 18). In the case of ground handling, rebound, and retraction conditions, design limit loads are defined. In the case of landing conditions, design landing loads are defined. Both design limit and design landing loads correspond in magnitude to the maximum expected operating loads.

The specification requires that a factor of safety of 1.5 be applied between the design limit and the design ultimate loads, where ultimate magnitudes are those which would cause collapse of the structure. In the case of design landing loads, no ultimate factor of safety is specified. Instead, the specification requirement is that the cumulative effects of elastic, permanent, and thermal deformations, which result from the application of the design landing loads, shall not interfere with the mechanical operation of the landing gear (Reference 17, Paragraph 3.1.4 and Reference 18, Paragraph 3.1.3). In essence, this says that the gear may be loaded to higher load levels with no limit on plastic and permanent deformations as long as the assembly continues to perform its function in a normal fashion.

With conventional metallic structural materials, ductility provides sufficient additional reserve strength, due to the ability to redistribute localized loadings, to provide a substantial margin of safety between maximum landing loads and collapse loads. With filament composite materials this is not true - large deformations do not occur until filament failure is initiated, at which load level the composite structure is very near its rupture strength. To provide a suitable strength reserve it was decided to treat landing loads the same as limit loads and to provide a factor of safety of 1.5 between design and collapse (or ultimate) loads.

The structural design criterion, then, was to design for ultimate loads for all load conditions, using ultimate, or rupture, strength envelopes for laminate strength. To accommodate this philosophy, design load tables and laminate strength allowables are reported for ultimate strength levels.

### 4.5.2 Margins of Safety

The axle, piston, outer cylinder, and trunnion of the existing A-37B landing gear were fabricated from steel heat treated in the 180-200 ksi UTS range. For a valid weight comparison, any steel parts in the filament composite gear should also be heat treated

to this same strength level. The use of higher strength steel parts would result in additional weight reductions which would mask the actual weight savings attributable to the introduction of the filament composite materials.

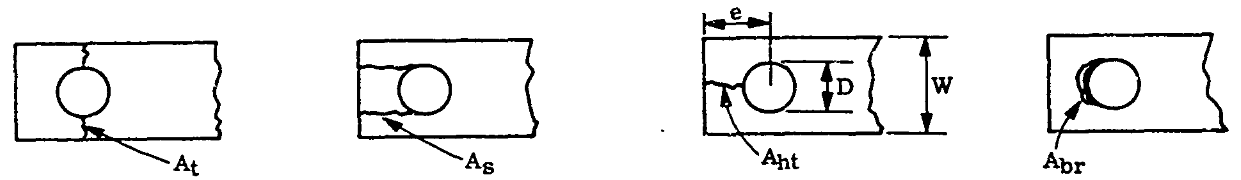
However, the stress analysis report (Reference 12) associated with the existing steel gear indicates margins of safety in many cross-sections averaging a negative 15 percent. These negative margins arose from increasing the aircraft gross weight from 12,000 to 14,000 pounds without a corresponding increase in gear strength. These negative margins were justified on the grounds that the landing gear successfully sustained static test loads corresponding to the 14,000 pound aircraft (Page v, Reference 12).

Negative margins, however, result in an unfair weight advantage for the current steel gear over the filament composite gear which was being designed to a zero margin of safety. One could compensate by also designing the composite assembly to a negative 15 percent margin; however, this would increase the chances of a premature failure during the structural design testing of the filament composite assembly. Therefore, it was decided to compensate for the weight advantage of the existing gear by designing and fabricating all steel parts in the filament composite assembly to the 220-240 ksi UTS range.

## TABLE 4-4. SUMMARY OF PIN BEARING TESTS

**Failure Modes**

Tension = T　　Shear = S　　Hoop = H　　Bearing = B




$A_t = (W-D)t$　　$f_t = P/A_t$

$A_s = 2\,et$　　$f_s = P/A_s$

$A_{ht} = (e-D/2)t$　　$f_{ht} = \frac{P}{2A_{ht}}$

$A_{br} = Dt$　　$f_{br} = \frac{P}{A_{br}}$

| Specimen No. | D in. | t in. | e in. | W in. | $A_t$ in.$^2$ | $A_{ht}$ in.$^2$ | $A_s$ in.$^2$ | $A_{br}$ in.$^2$ | Load lbs. | $f_t$ ksi | $f_{ht}$ ksi | $f_s$ ksi | $f_{br}$ ksi | Failure Mode |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PBA-1-1 | .688 | .094 | .850 | 1.196 | .048 | .048 | .160 | .065 | 1917 | 40.1 | 20.1 | [illegible] | 29.6 | T |
| PBA-1-2 | .688 | .094 | .850 | 1.196 | .048 | .048 | .160 | .065 | 1962 | 41.1 | 20.6 | 12.[illegible] | 30.3 | T |
| PBA-2-1 | .688 | .093 | .850 | 1.185 | .046 | .047 | .157 | .064 | 1724 | 37.4 | 18.4 | 10.9 | 27.1 | T |
| PBA-2-2 | .688 | .093 | .850 | 1.185 | .046 | .047 | .157 | .064 | 1640 ① | 35.6 | 17.5 | 10.4 | 25.7 | T |
| PBE-0-1 | .625 | .1035 | .610 | 1.198 | .059 | .031 | .126 | .064 | 2535 | 42.7 | 41.2 | 20.1 | 39.2 | H |
| PBE-0-2 | .688 | .1035 | .853 | 1.198 | .052 | .052 | .176 | .071 | 4490 | 85.0 | 42.6 | 25.4 | 63.1 | T |
| PBE-1-1 | .625 | .1035 | .609 | 1.199 | .099 | .031 | .125 | .064 | 2880 | 48.4 | 47.1 | 22.8 | 44.5 | H |
| PBE-1-2 | .688 | .1035 | .855 | 1.199 | .052 | .052 | .177 | .071 | 4570 | 86.3 | 43.1 | 25.8 | 64.1 | T |
| PBE-2-1 | .625 | .1055 | .611 | 1.195 | .060 | .031 | .128 | .065 | 2930 | 48.7 | 46.6 | 22.7 | 44.4 | S |
| PBE-2-2 | .688 | .1055 | .853 | 1.195 | .053 | .053 | .180 | .072 | 4195 | 78.5 | 39.1 | 23.3 | 57.8 | S |
| PBE-3-1 | .625 | .106 | .610 | 1.20 | .060 | .031 | .129 | .066 | 1790 | 29.3 | 28.4 | 13.8 | 27.0 | H |
| PBE-3-2 | .688 | .106 | .854 | 1.20 | .054 | .054 | .181 | .072 | 3600 | 66.4 | 33.2 | 19.8 | 49.3 | T |
| PBE-4-1 | .625 | .1045 | .609 | 1.20 | .059 | .031 | .127 | .065 | 1845 | 30.8 | 29.8 | 14.5 | 28.2 | H |
| PBE-4-2 | .688 | .1045 | .852 | 1.20 | .053 | .053 | .178 | .071 | 3300 | 61.9 | 31.1 | 18.5 | 45.9 | H |

① Specimen slipped in grips prior to failure.　PBA = BORSIC-Aluminum　PBE = Boron-Epoxy

Hole Reinforcement:

PBA: ± 45° Cross Ply
PBE-0,1 and 2: Spiral
PBE-3 and 4: ± 45° Cross Ply

## SECTION V

## DESIGN OF LANDING GEAR COMPONENTS

### 5.0 INTRODUCTION

This section provides the results of the Phase I design and fabrication studies. The objective of these studies was to produce drawings and establish processing techniques to be used during Phase II for fabricating the boron composite landing gear assembly.

The discussion starts with a description of the conventional metallic landing gear components currently used on the A37B aircraft. This is followed by a discussion detailing the proposed designs for the filament composite versions of these components. Finally a summary is included of the characteristics of the metallic liners applied to the piston and outer cylinder tubes.

### 5.1 DESCRIPTION OF CONVENTIONAL A-37B COMPONENTS

This section describes the conventional landing gear components currently being used on the A-37B aircraft after which the boron composite hardware is patterned. The discussion includes the side brace, torque arms, outer cylinder, piston, and shock absorber assemblies.

#### 5.1.1 Side Brace

The conventional side brace assembly for the A-37B aircraft main landing gear is illustrated in Figures 1-1, 1-2, 1-3 and 5-1. This member supports the shock absorber in the side direction and reacts side loads applied at the ground. The brace consists of two links which fold to allow retraction and extension of the landing gear during flight. An over-center locking device is required at the hinge to lock the brace in the extended position. The side brace is pin connected at both ends so that, for the critical design condition it is subjected to axial loads only. Bending moments are also developed, however, due to initial eccentricities in the member. This member is designed for tension and compression strength in addition to column stability. The conventional members are fabricated from aluminum alloy forgings heat treated to 75 ksi UTS.

#### 5.1.2 Torque Arms

The conventional torque links for the A-37B main landing gear are illustrated in Figures 1-1, 1-2, and 5-2. The upper and lower links are shown in Figure 5-2 to indicate the similarity of the two members. Torsion is produced by the offset of the wheel from the shock absorber center line. This load is transmitted by the torque links from the lower

piston to the outer cylinder. Each torque link member is designed by side loads applied in the plane of the member at the knee lug (the single lug). The loading may act in either direction. The loading condition requires that the torque link have high compressive and tensile properties along each flange as well as high in-plane transverse shear strength. The torque links are fabricated from 4340 steel forgings and heat treated to 180-200 ksi UTS.

### 5.1.3 Outer Cylinder

The conventional outer cylinder-trunnion assembly for the A-37B main landing gear is illustrated in Figures 1-1, 1-2 and 5-3. This item is fabricated from a 4340 steel forging and heat treated to 180-200 ksi UTS. This is the largest component in the landing gear and also the most complicated, geometrically. At the lower end, fittings are required to support the torque link lugs and the packing retainer plate. The center of the cylinder is fitted with side brace lugs, aircraft tie-down rings and a boss for the landing gear door attachment. The upper end of the cylinder is fitted with two I-section trunnion arms. The governing loads include bending, torsion, axial, shear and internal pressure loadings. In general, these loads are applied concurrently.

Any assembly constructed from composite materials must, of course, be capable of performing the same functions, supporting the same loads and interfacing with the same supporting structure as the existing outer cylinder assembly. The composite design must, therefore, incorporate the same fittings, lugs, rings and bosses as are included in the existing design. The attachment of these fittings and parts is complicated by the requirement that the inside surface of the cylinder be unobstructed to permit stroking of the piston. In addition, the cylinder wall must be impervious to hydraulic fluid under pressure and the inner surface must be hardened to resist wear due to the piston bearing.

### 5.1.4 Piston

The conventional piston-axle assembly for the A-37B main landing gear is illustrated in Figures 1-1, 1-2 and 5-4. This item is fabricated from steel alloy heat treated to 180-200 ksi UTS. The axle is a separate member from the piston, the two being joined at the axle socket which is an integral part of the piston. The assembly includes a jacking point, a shock absorber metering pin and an upper main bearing. The governing loads for cylinder design include bending, shear and internal pressure loadings.

As with the outer cylinder, a composite piston design must incorporate a number of hardware fittings. Likewise, the cylinder wall must resist penetration by hydraulic fluid and the surface hardened to resist wear due to the outer cylinder bearing.

### 5.1.5 Shock Absorber Assembly

The conventional shock absorber assembly comprising the outer cylinder-trunnion, the piston-axle, the torque arm, and various internal fittings is illustrated in Figures 5-5 and 5-6.

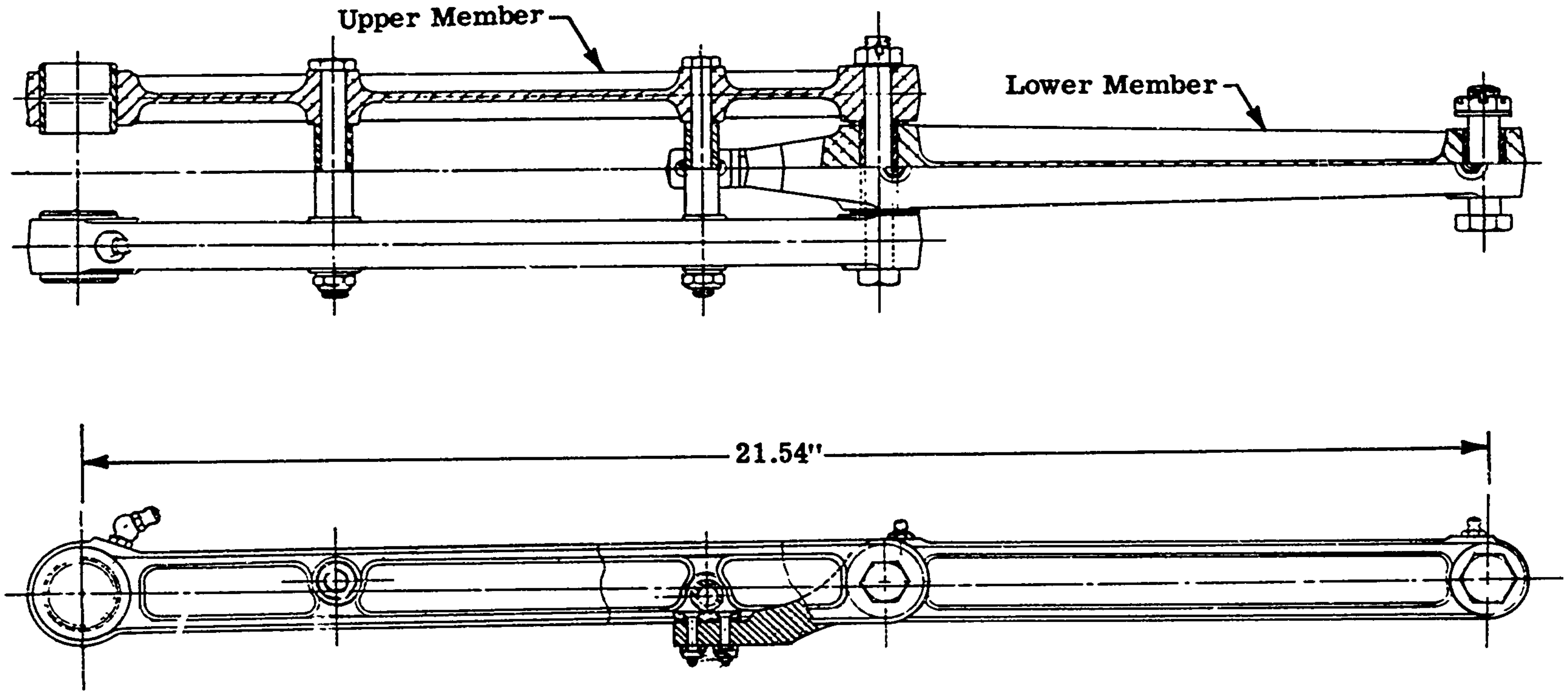
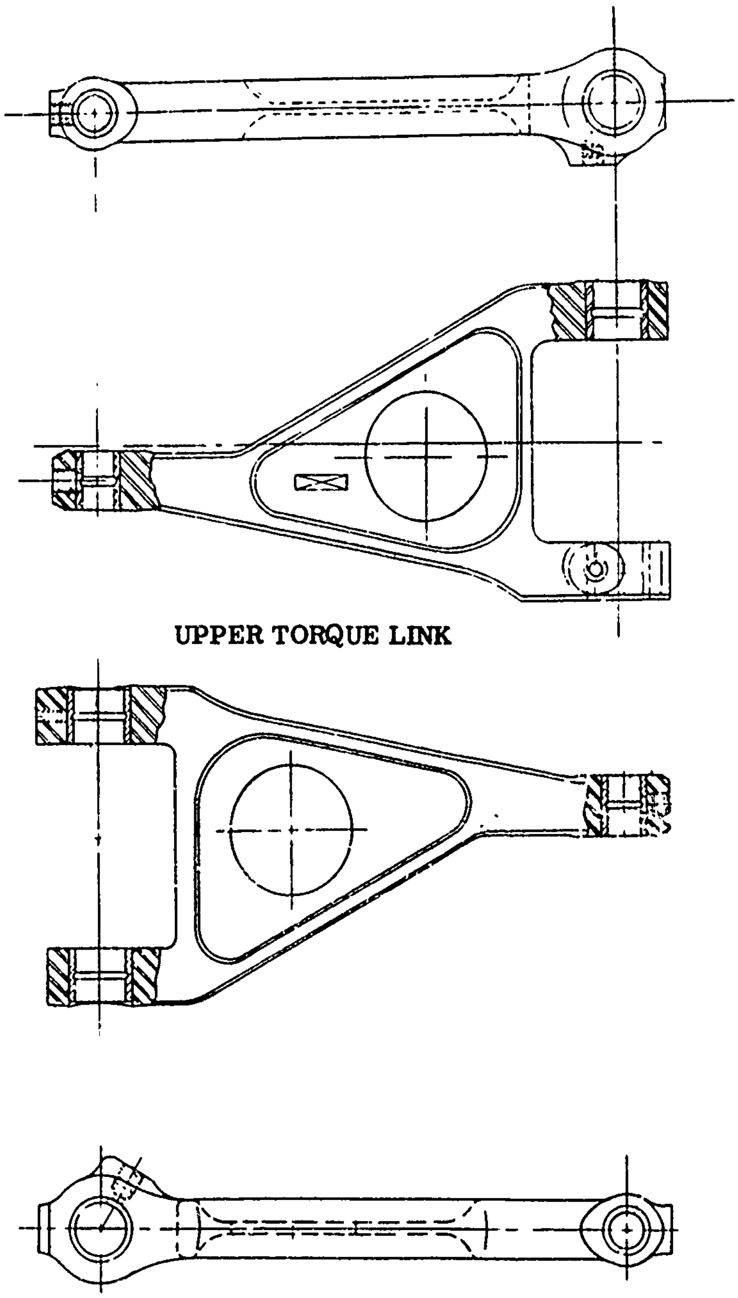



Figure 5-1. Conventional Side Brace




LOWER TORQUE LINK

Figure 5-2. Conventional Torque Links

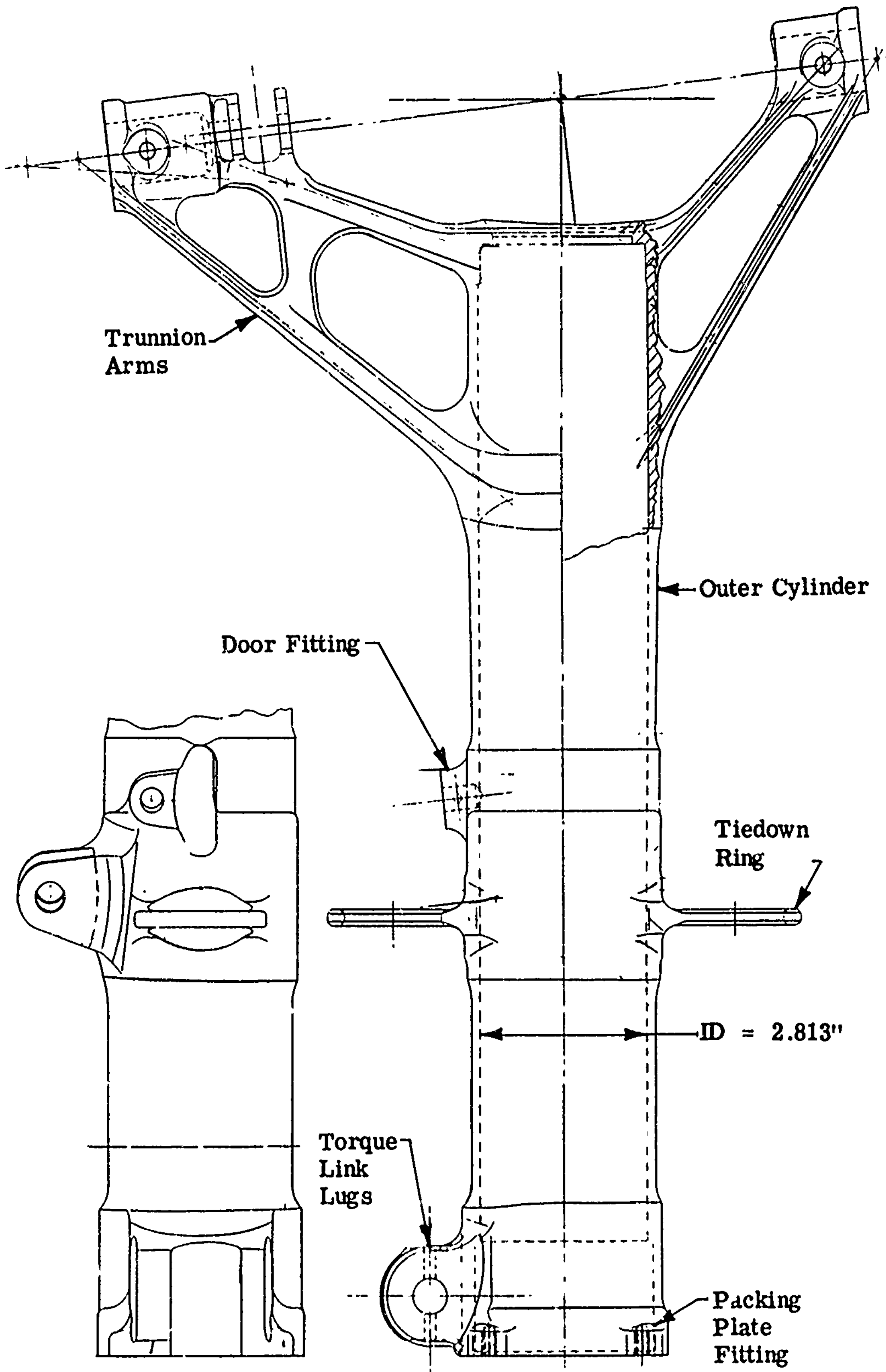



Figure 5-3. Conventional Outer Cylinder

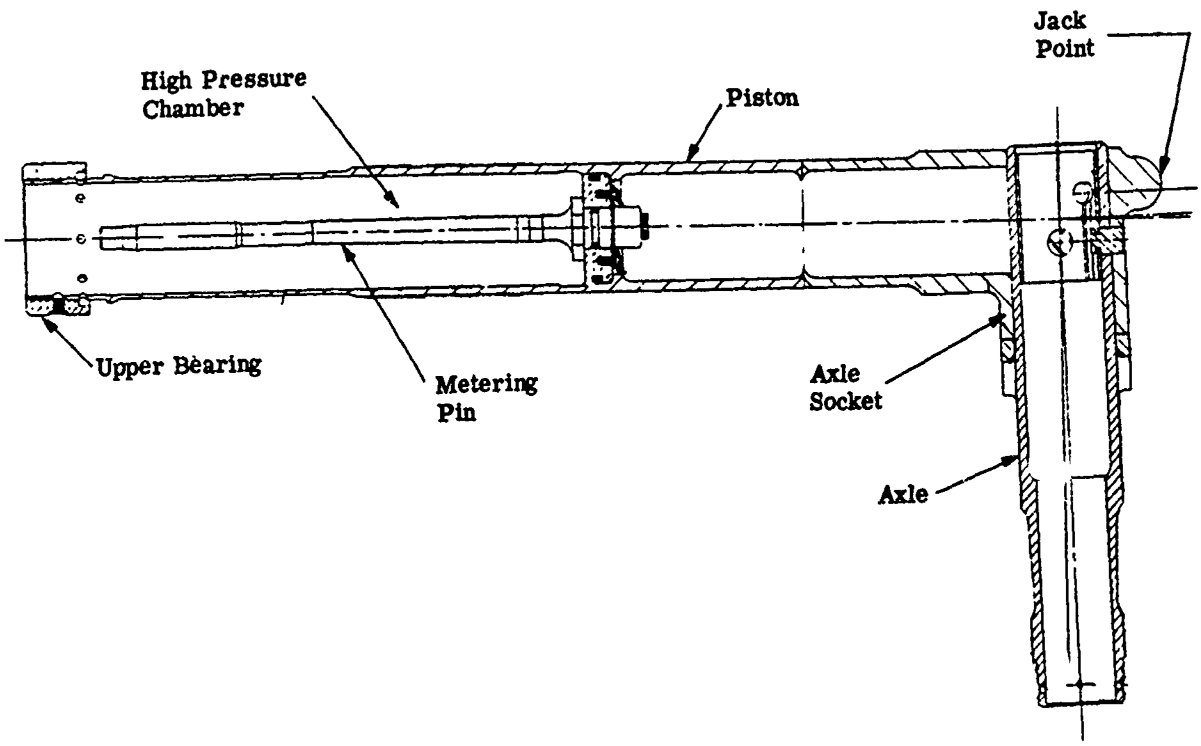



Figure 5-4. Conventional Piston-Axle Assembly

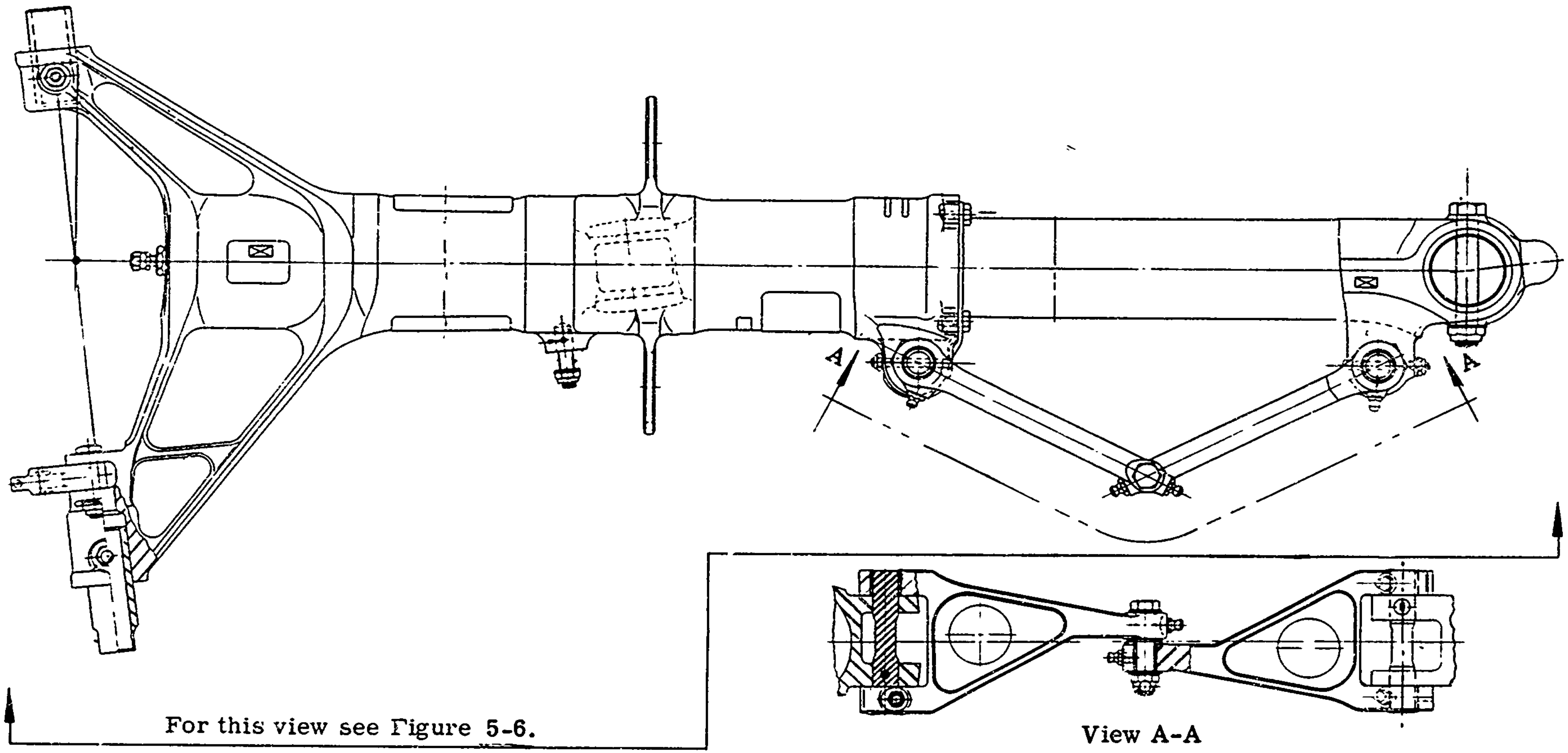



Figure 5-5. Conventional Steel Shock Absorber Assembly

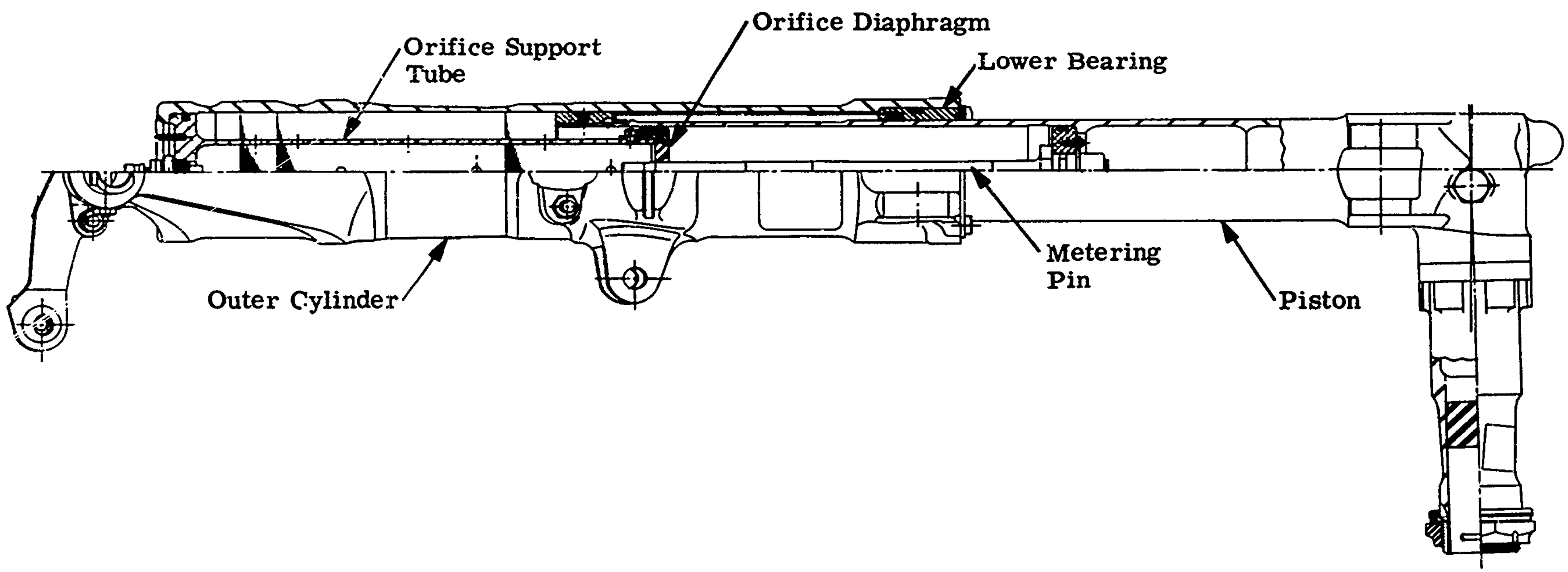



Figure 5-6. Conventional Steel Shock Absorber Assembly

## 5.2 FILAMENT COMPOSITE DESIGNS

This section describes the design details of the individual boron composite components proposed for Phase II fabrication. The first part of the discussion deals with the BORSIC-aluminum components and the second with the boron-epoxy designs. The description covers the side brace, torque arms, outer cylinder and piston in that order. In addition to the prototype component designs, the discussion covers the design and testing of a number of design support trial specimens. The processing details pertaining to both the prototype and the trial specimen fabrication are given in Section VIII of this report.

### 5.2.1 BORSIC-Aluminum Designs

This paragraph deals with the design of the prototype components and the results of tests performed on the design support specimens. Material sources and the fabrication and processing details are given in Paragraph 8.1.

#### 5.2.1.1 BORSIC-Aluminum Side Brace

Two design concepts were studied in detail. The first concept, which involved a box shaped cross section, was abandoned because of fabrication difficulties encountered with the trial specimens. The finally proposed design incorporated an I shaped cross section.

Box Shaped Design - Brace Assembly

This design is illustrated in Figures 5-7, 5-8 and 5-9.

Each of the three primary side brace components consists of four panels supported by inserts required for transmitting pin loads. The primary load carrying panels (flanges) consist of plates with the filaments oriented in the axial, or loaded, direction. The side panels, required for stabilizing the flanges and for transmitting transverse shear loads, are composed of a ±45° cross ply pattern. The lug ends and pin support inserts also consist of ±45° cross ply layups.

The panels and fitting inserts were designed to be fabricated individually and machined prior to assembly. The individual BORSIC-aluminum pieces were then to be assembled into a single side brace component by one brazing operation. The brazing operation would be followed by final machining and application of miscellaneous fittings such as bushings, shims, pins, and spacers.

The fabrication details associated with this design are similar to those described in Paragraph 8.1.3.1 for the trial specimens.

Box Shaped Design - Trial Specimens

Two BORSIC-aluminum side brace specimens of the configuration illustrated in Figure 5-10 were fabricated and tested. These specimens were intended to simulate the side brace concepts illustrated in Figures 5-7 through 5-9.

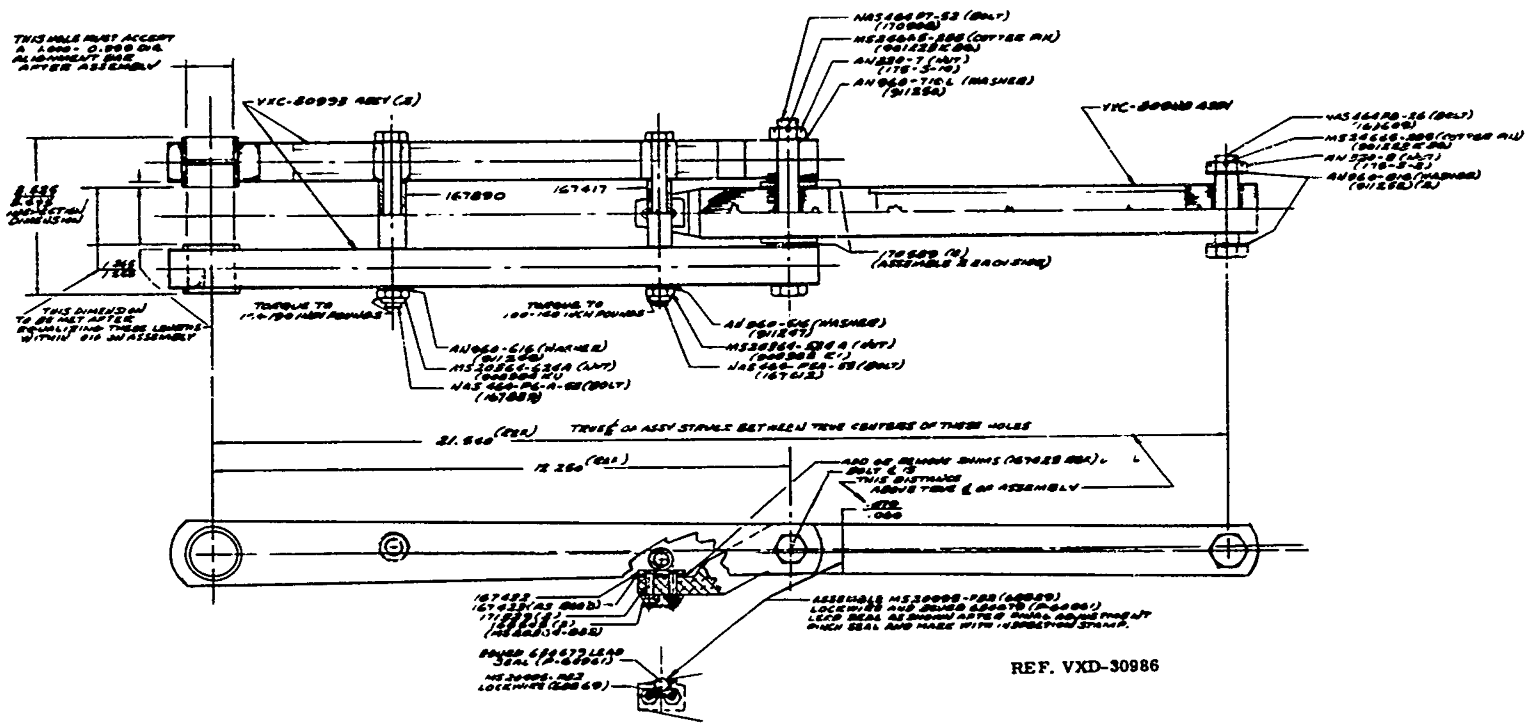
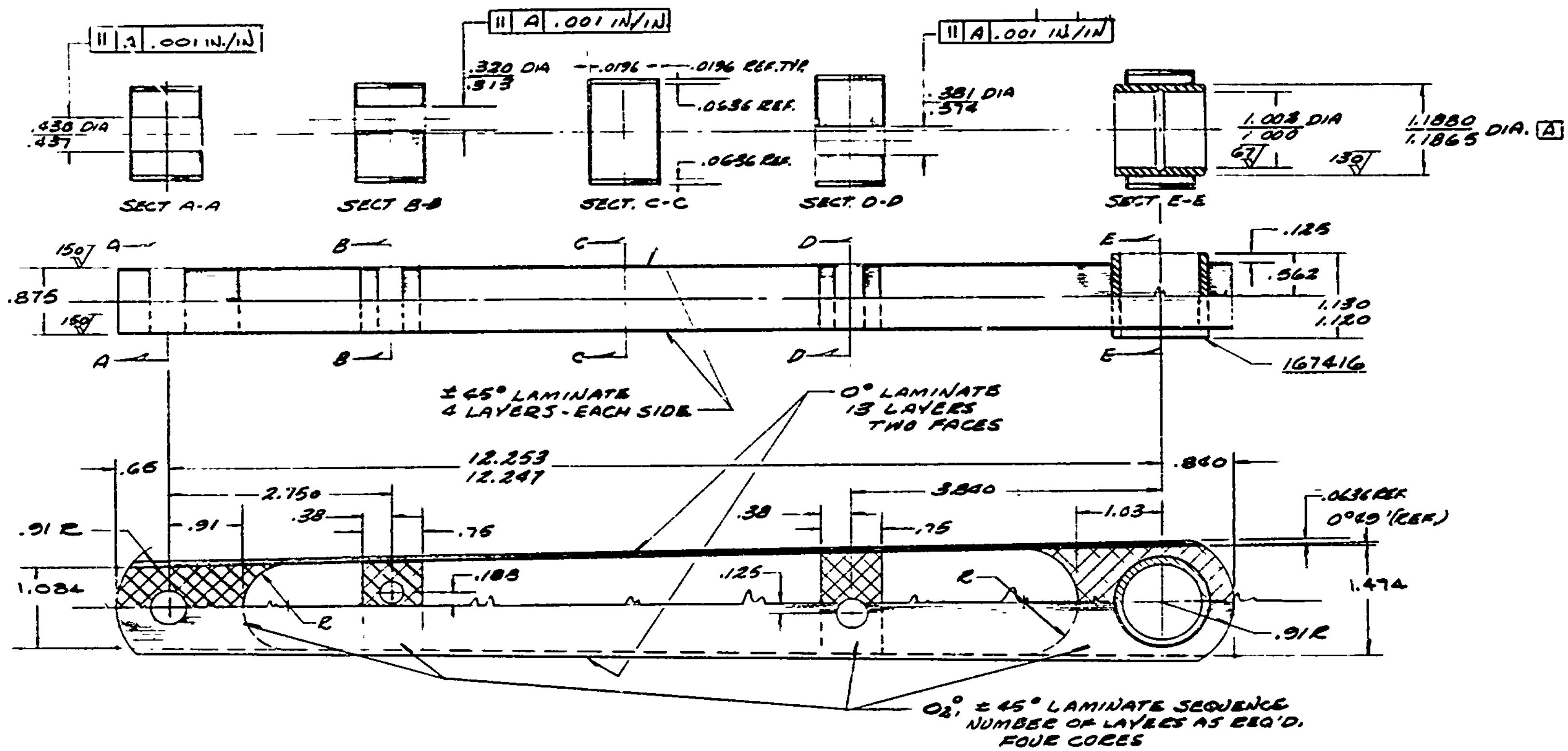
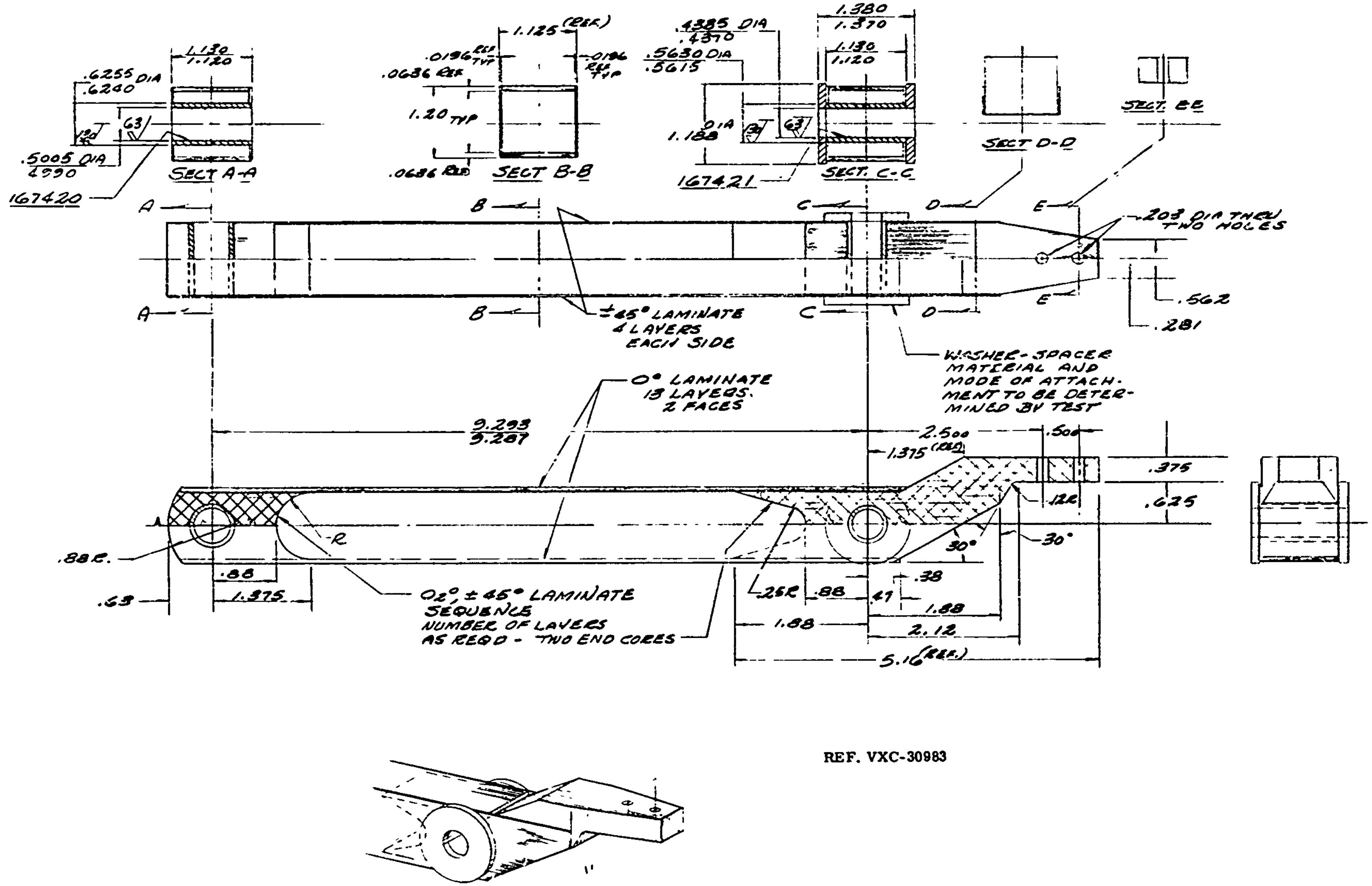



Figure 5-7. BORSIC-Aluminum Side Brace Assembly (Proposed only-not fabricated)




REF. VXC-30993

Figure 5-8. BORSIC-Aluminum Upper Side Brace Member (Proposed only-not fabricated)




REF. VXC-30983

Figure 5-9. BORSIC-Aluminum Lower Side Brace Member (Proposed only-not fabricated)

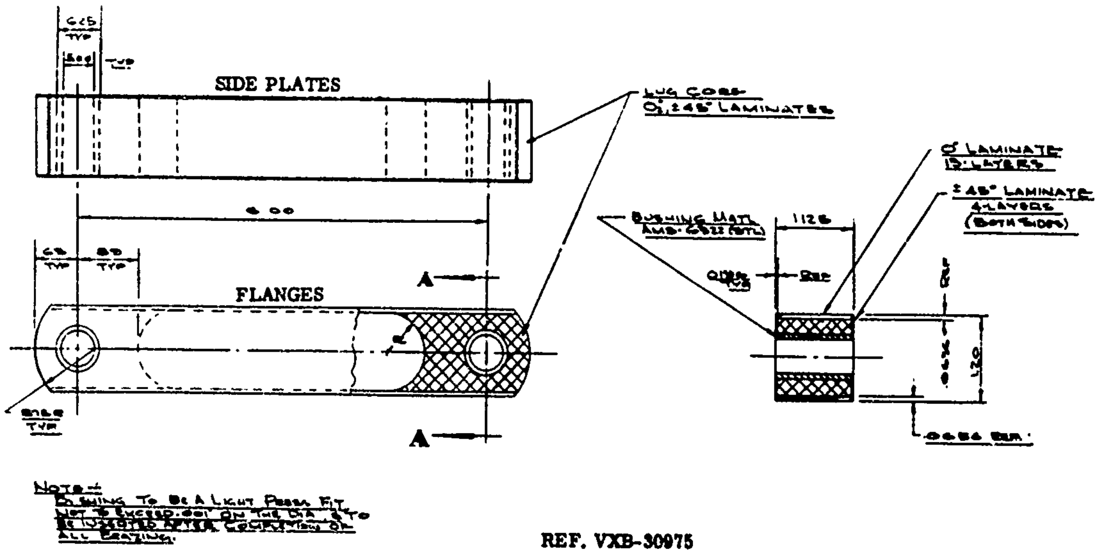



Figure 5-10. BORSIC-Aluminum Side Brace Specimen

The fabrication details for these specimens are given in Paragraph 8.1.3.1.

The test instructions for the brace specimens may be summarized as follows:

> Step 1 - Load in tension to the design limit load of 9200 pounds on the first specimen and 8900 pounds on the second specimen. (The different loads are due to a slight difference in construction of the lug ends between the two specimens.)
>
> Step 2 - Load in compression to the design ultimate load of 29,800 pounds.

The first of these specimens to be built by Hamilton Standard is illustrated in Figure 5-11. This specimen was tested by Hamilton Standard who reported the results as follows:

> "The specimen was strain gaged as shown in Figure 5-11. Gages were placed around the bearing area, four per side and one gage at the center of each rail. Gages 6 and 12 were located on the load carrying 0° oriented rails (panels). The specimen was assembled in the Tinius-Olsen test machine and subjected to a tensile load.
>
> The Plan of Test prescribed that during the tensile loading, the specimen be subjected to a maximum load of 9200 pounds, with strain readings being recorded every 900 pounds. A failure occurred at 4190 pounds well below the required test load. Failure occurred in the 0° side rail and propagated through the adjacent ±45° rails, see Figures 5-12, 5-13 and 5-14.

Investigation of the strain gage data revealed that gage 6 was measuring a strain greater than that of the opposite panel, gage 12. Extrapolation of the strain to the fracture load disclosed a tensile strength of 52,500 psi.

Investigation for the reason that a bending load was applied to the specimen revealed that a fault in the composite rail existed. Examination of a photograph of the specimen prior to test revealed two faults, a longitudinal one emanating from the lower left corner of gage 6 and one from the edge of the panel to the lower left corner of the same gage. The reason that this was not noted prior to gaging is that it was not visible. To prepare the surface for the gage, this area was sanded. It is believed that the operation removed enough of the 6061 layer to make these faults visible. Examination of the fracture area, Figures 5-15, 5-16 and 5-17 reveals the fact that broken and oriented fibers are in evidence to the longitudinal fault. The trimmed laminate from the panel which the side rail was cut from also had evidence of the fault and the condition is believed to have further been aggravated during the brazing of the component into the side brace structure when a slight dent was introduced in the same area."

A second side brace specimen was fabricated for the purpose of repeating the test. This specimen was identical to the first except that in the first case the flanges overlapped the side plates.

The specimen was loaded successfully to the required tension load of 8900 pounds. During application of the compression load, buckling failure occurred at 13,400 pounds, Figure 5-18.

The premature failure of the second side brace specimen was attributed primarily to the inadequate braze condition in the corner joint between the side plates and the flanges. This condition is illustrated in Figure 5-19 where lack of braze flow into the upper corner joint is evident. This condition apparently resulted in early separation of the two panels and the consequent lack of support for the flange precipitated buckling of this main load carrying member.

The outcome of this fabrication trial and structural test indicated the necessity of facilitating braze flow in the corner joints. A feasible technique for accomplishing this involves the application of small aluminum angles in the corners. The application of such angles is difficult here because of the enclosed box section. This obstacle was overcome by moving the side plates together to form an I-section so that the angles can be more conveniently applied to an outside surface.

I-Shaped Design - Brace Assembly

An improved design for the BORSIC-aluminum side brace is illustrated in Figures 5-20, 5-21 and 5-22. The upper and lower members consist of I-sections which transmit axial loads through pinned joints at each end. The flanges consist primarily of axially oriented filaments with a layer of transverse filaments on each surface to provide lateral stability of the plates. The web consists of ±45° crossply layup. The purpose of the aluminum corner angles is to facilitate brazing of the web to the flanges. The buildup for the joint lugs and for the centerlock extension consists of $0_2°$, ±45° crossply layup.

Fabrication and processing details for this design are described in Paragraph 8.1.3.2.

The I-shaped concept illustrated in Figures 5-20, 5-21 and 5-22 is the one finally proposed for fabrication and testing in Phase II.

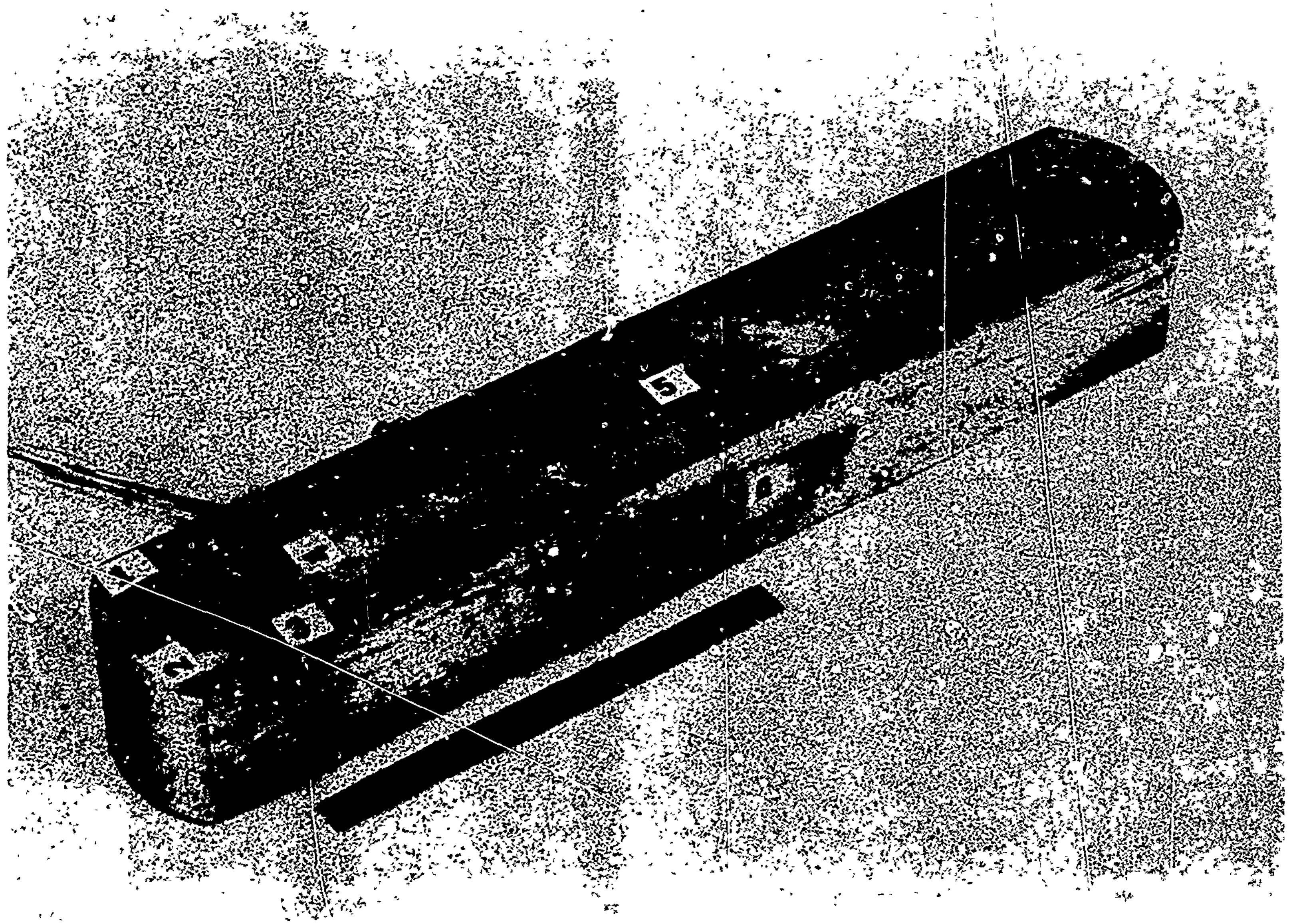


Figure 5-11. BORSIC-Aluminum Side Brace - First Specimen

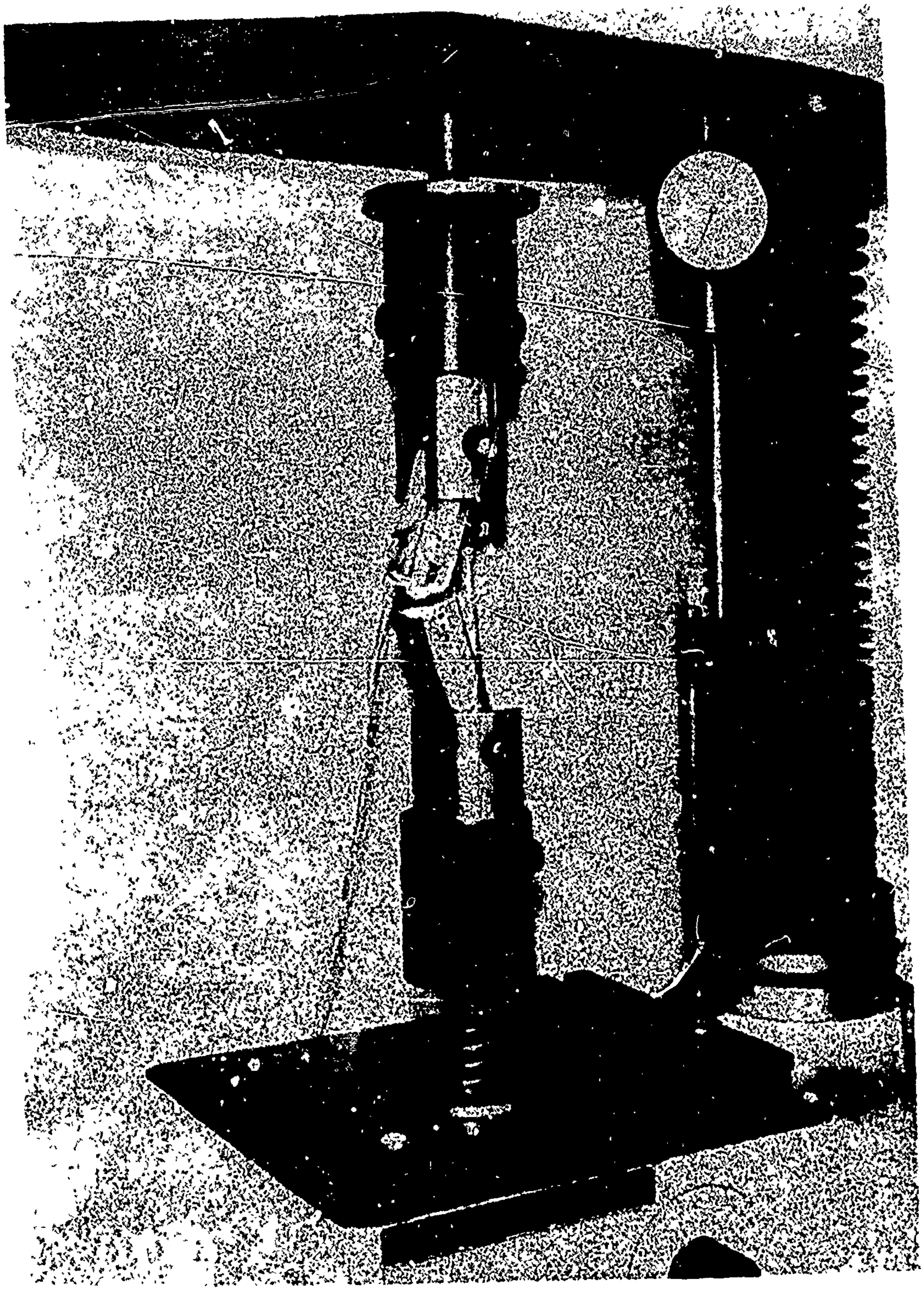


Figure 5-12. Side Brace Fractured in Test Assembly

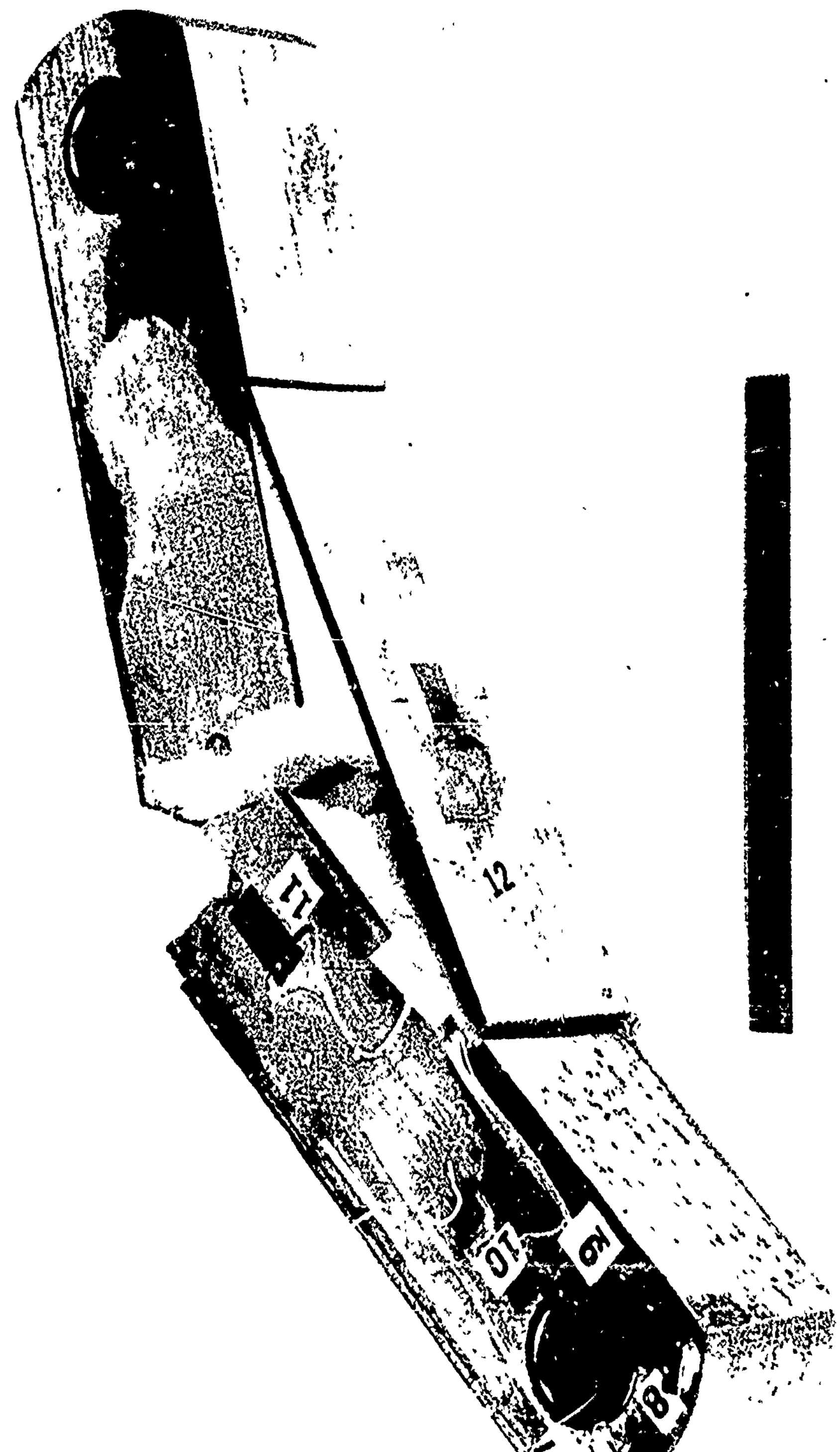


Figure 5-13. Side Brace Fractured

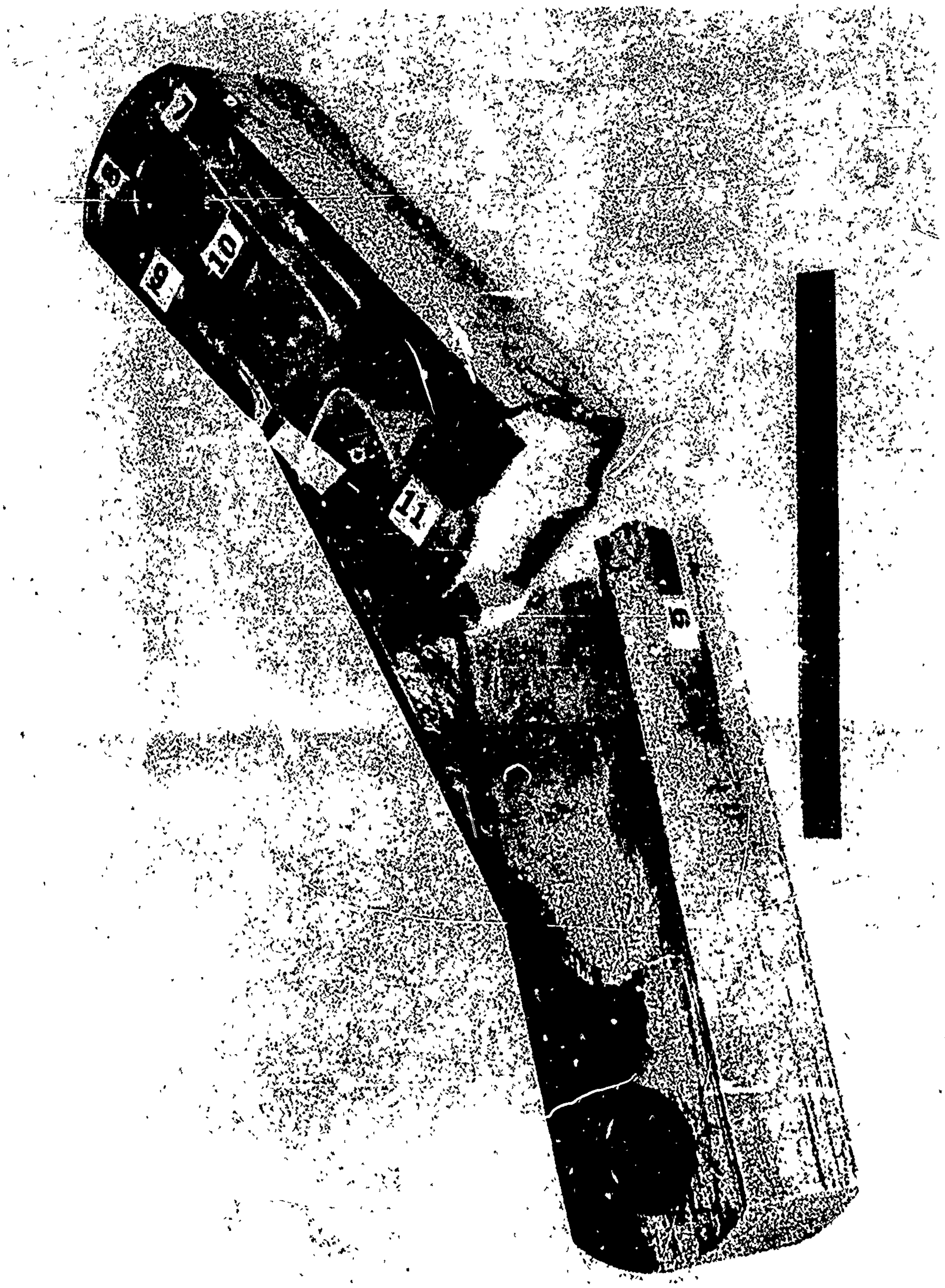


Figure 5-14. Side Brace Fractured

Figure 5-15. Fractured Area - 10X Magnification

Figure 5-16. Fractured Area

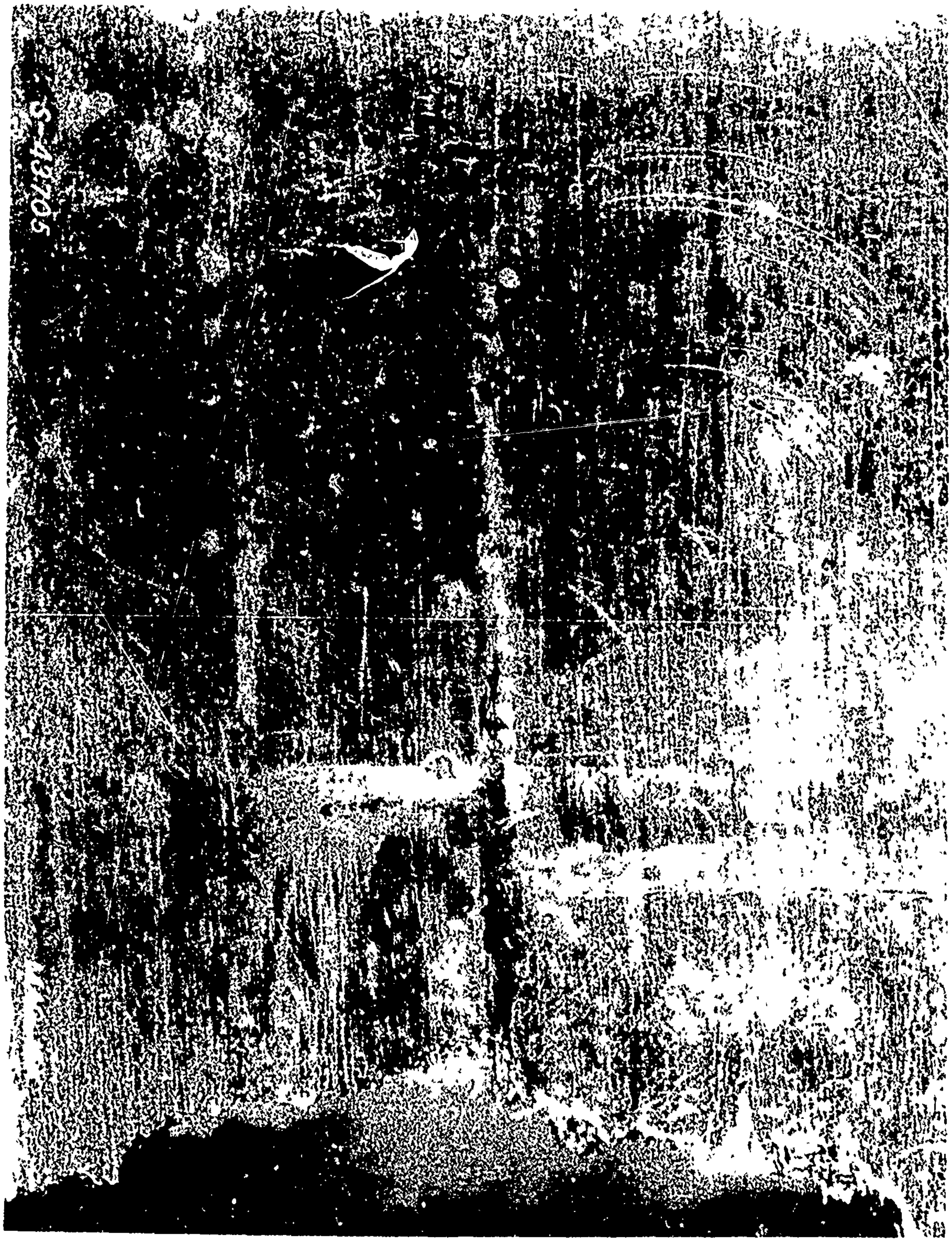


Figure 5-17. Fractured Area - Longitudinal Fault

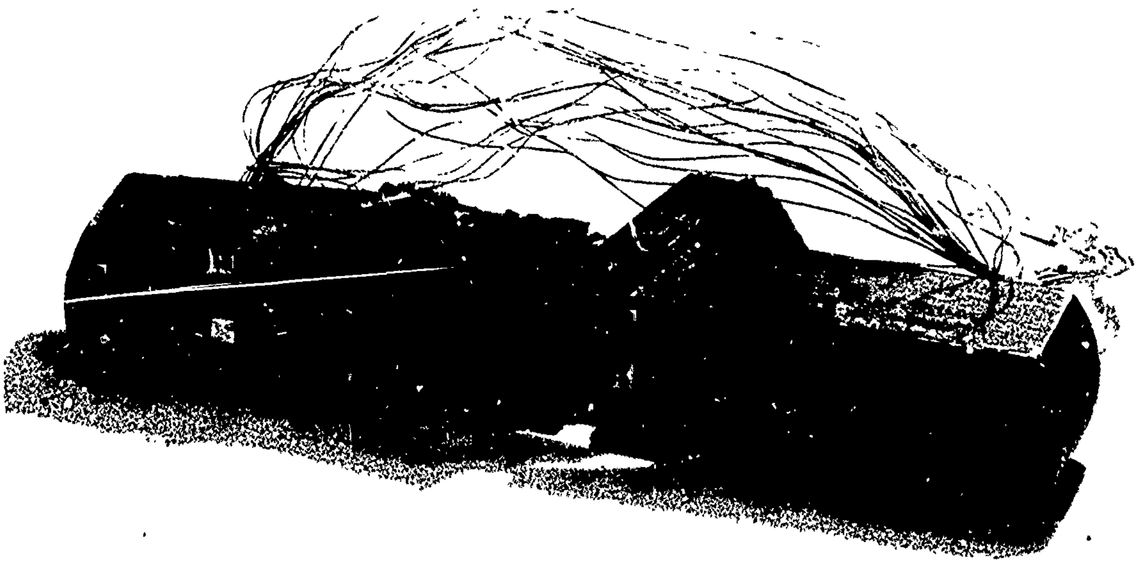
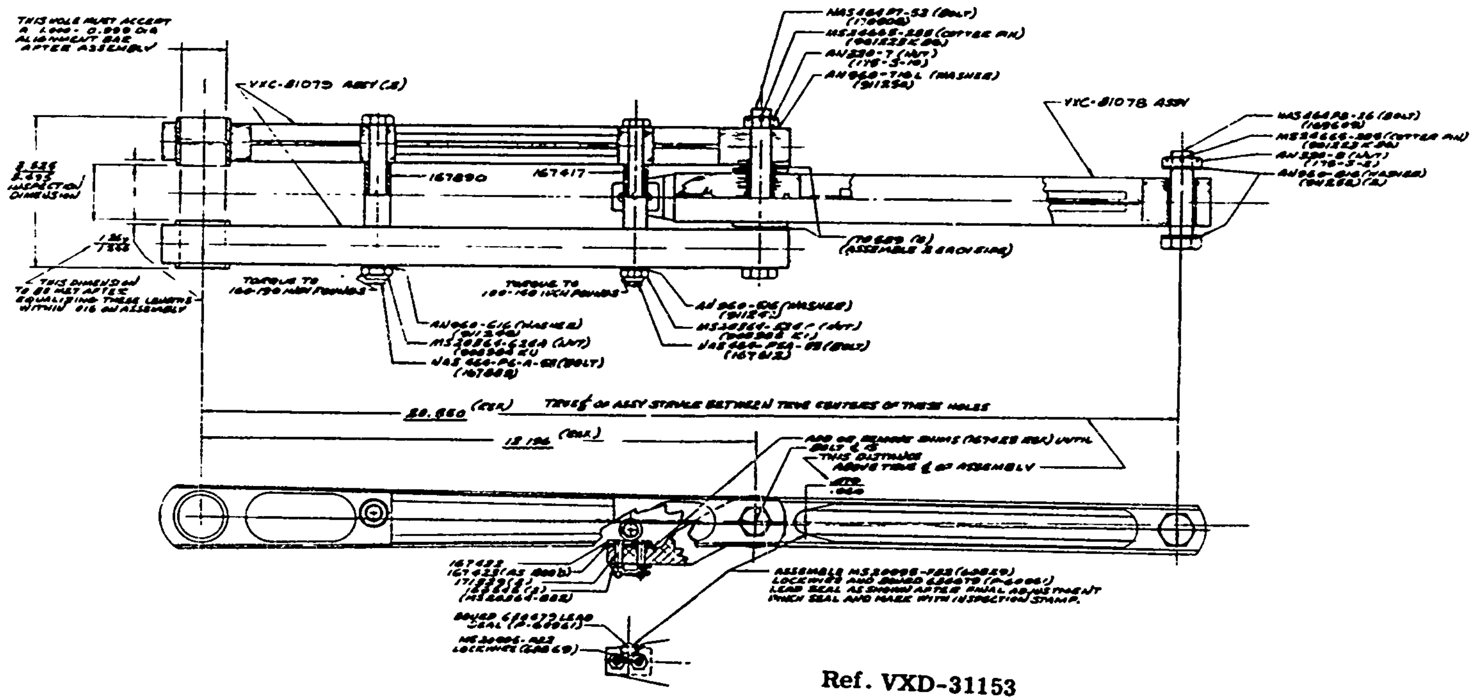


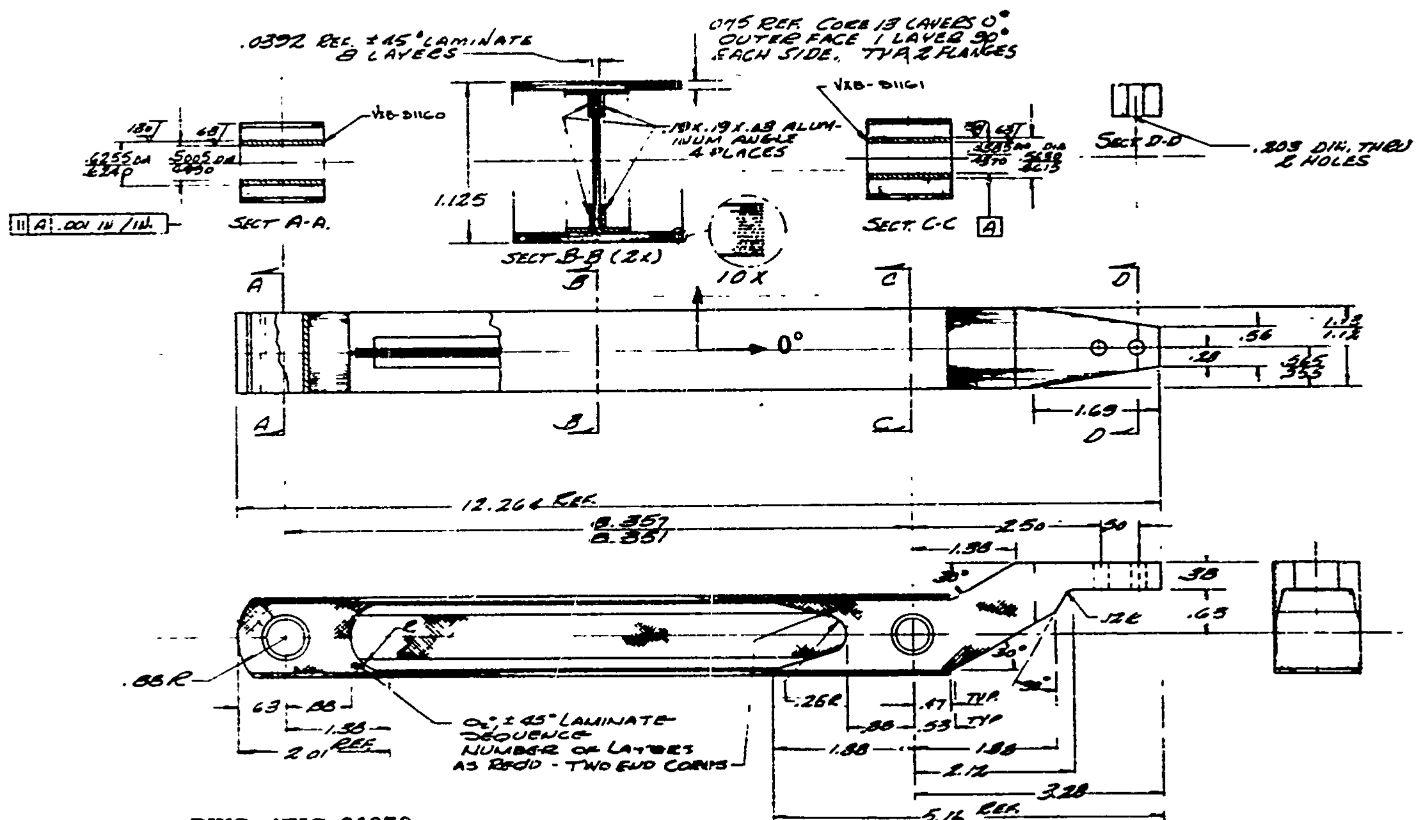
Figure 5-18. BORSIC-Aluminum Side Brace - Second Specimen

Figure 5-19. Corner Braze Detail



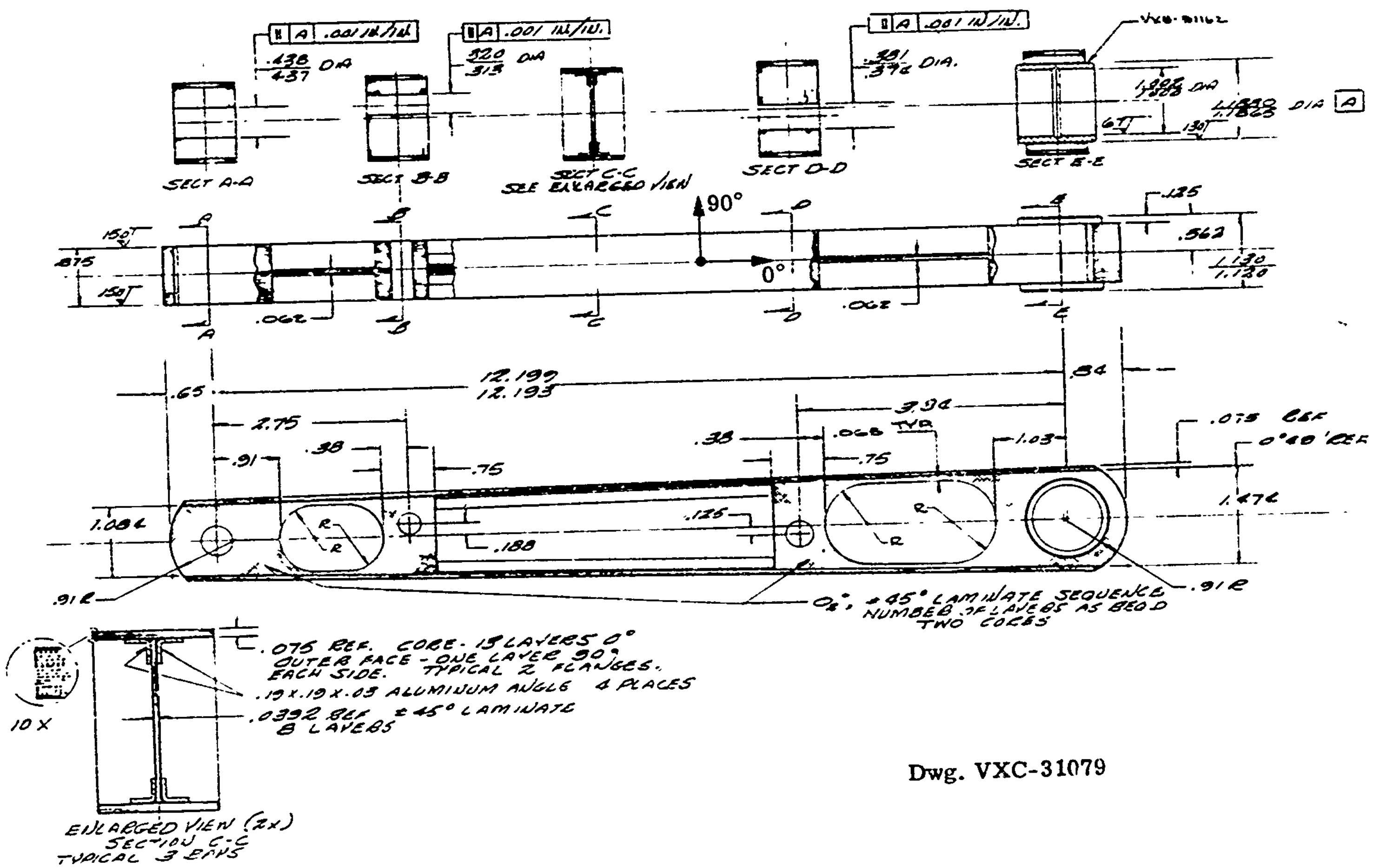

Ref. VXD-31153

Figure 5-20. Side Brace Assembly, BORSIC-Aluminum (Proposed Design)




DWG. VXC-31078

Figure 5-21. Side Brace Lower Link, BORSIC-Aluminum (Proposed Design)




Dwg. VXC-31079

Figure 5-22. Side Brace Upper Link, BORSIC-Aluminum (Proposed Design)

### 5.2.1.2 BORSIC-Aluminum Torque Arms

The primary study effort was concentrated on the design shown in Figure 5-23.

Design Details - Trial Specimens

The construction details of this design are illustrated in Figures 5-23 through 5-26.

This design consists of a BORSIC-aluminum shell brazed to a titanium end fitting. The knee lug consists of a ±45° crossply core designed to support shearing due to the transverse knee load. The flanges, or rails, consist of filaments disposed along the length of the flange, the direction of primary load path. The ±45° crossply plates provide shear transfer between the flanges.

The metallic end fitting was selected because the BORSIC-aluminum composite does not have adequate tear out strength to resist the concentrated root lug loading. Titanium was selected for this fitting since this alloy provides the required structural strength and resists the brazing temperature without loss of strength. Also titanium has a coefficient of expansion which is compatible with that of the BORSIC-aluminum composite which is necessary during the brazing cycle.

The gradual taper of the flanges along the brazed joint is required to minimize the shear stress concentration along the bond line as the load transfers from one member to the other.

This concept performed very well during specimen fabrication and structural test trials.

#### Fabrication Details - Trial Specimens

The processing procedures associated with the fabrication of the trial torque arm assembly are described in Paragraph 8.1.4.

#### Test Results - Trial Specimens

A summary of the structural test requirements is given in Figure 5-27. These loads are of the same magnitude as the design loads ($Y_k$) tabulated in Table 4-1.

Two torque arm specimens were built by Hamilton Standard. The first assembly was built on an in-house effort as a specimen to check out processing techniques. This trial specimen was also employed in the loading rig for a brittle lacquer analysis, Figure 5-28, to determine the best locations for the strain gages to be applied to the second structural specimen. The strain gage applications are illustrated in Figures 5-29 and 5-30, and the test setup is shown in Figure 5-31.

The structural specimen successfully sustained the first two loading steps of Figure 5-27. During the third step the specimen failed at a load of $P_1$ = 3000 pounds with the result illustrated in Figure 5-32. The rupture occurred at point A in Figure 5-23 and was due to a tension failure of the 0.1175 inch thick BORSIC-aluminum flange.

An analysis to justify the premature failure was made. A review of the stress-coat and strain gage data and of the original design stress analysis revealed two design discrepancies.

1. The original theoretical design strength analysis relied on a 140 ksi tensile strength for this material, reference Table 4-3. Subsequent tensile data indicate a reduction in strength due to exposure to additional brazing cycles, reference Figures 4-3 and A-1. Based on the process employed for making the torque arms in three brazing cycles (a total of 75 minutes at braze temperature), a 116 ksi tensile strength would be selected from Figure A-1. This would require an increase in flange thickness.

2. During the original design stress analysis performed by Bendix an error was made in calculating the load to be carried by the flange, the error resulting in predicting a load lower than the actual. This error would require an additional increase in flange thickness.

Design Details - Prototype Assembly

Taking into account what was learned from the fabrication and structural test trial, the torque arm was redesigned with the result shown in Figure 5-33. This is the design proposed for Phase II fabrication.

Fabrication Details - Prototype Assembly

The fabrication and processing details proposed for the assembly of Figure 5-33 are outlined in Paragraph 8.1.4.2.

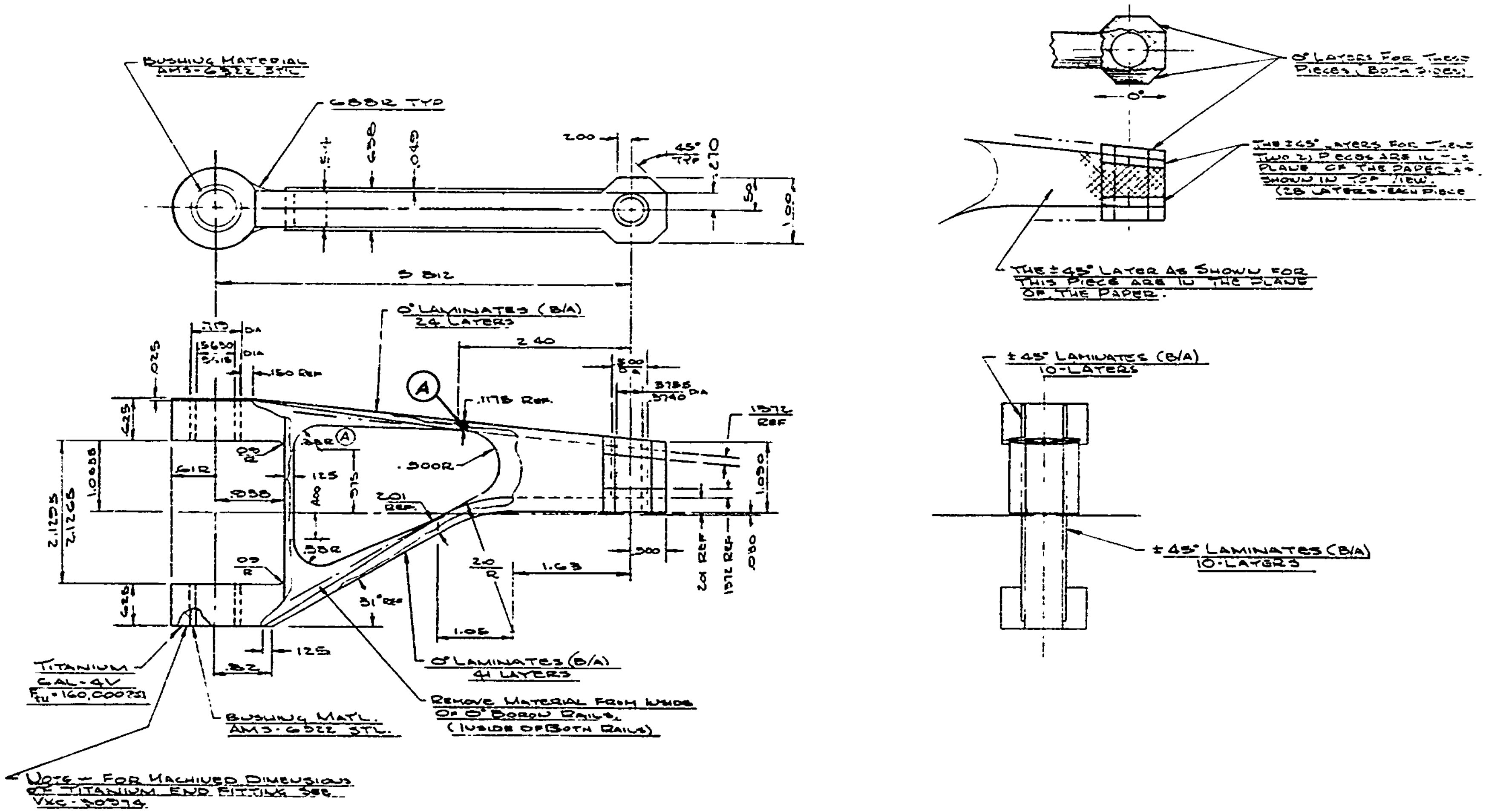



Figure 5-23. BORSIC-Aluminum Torque Arm Specimen

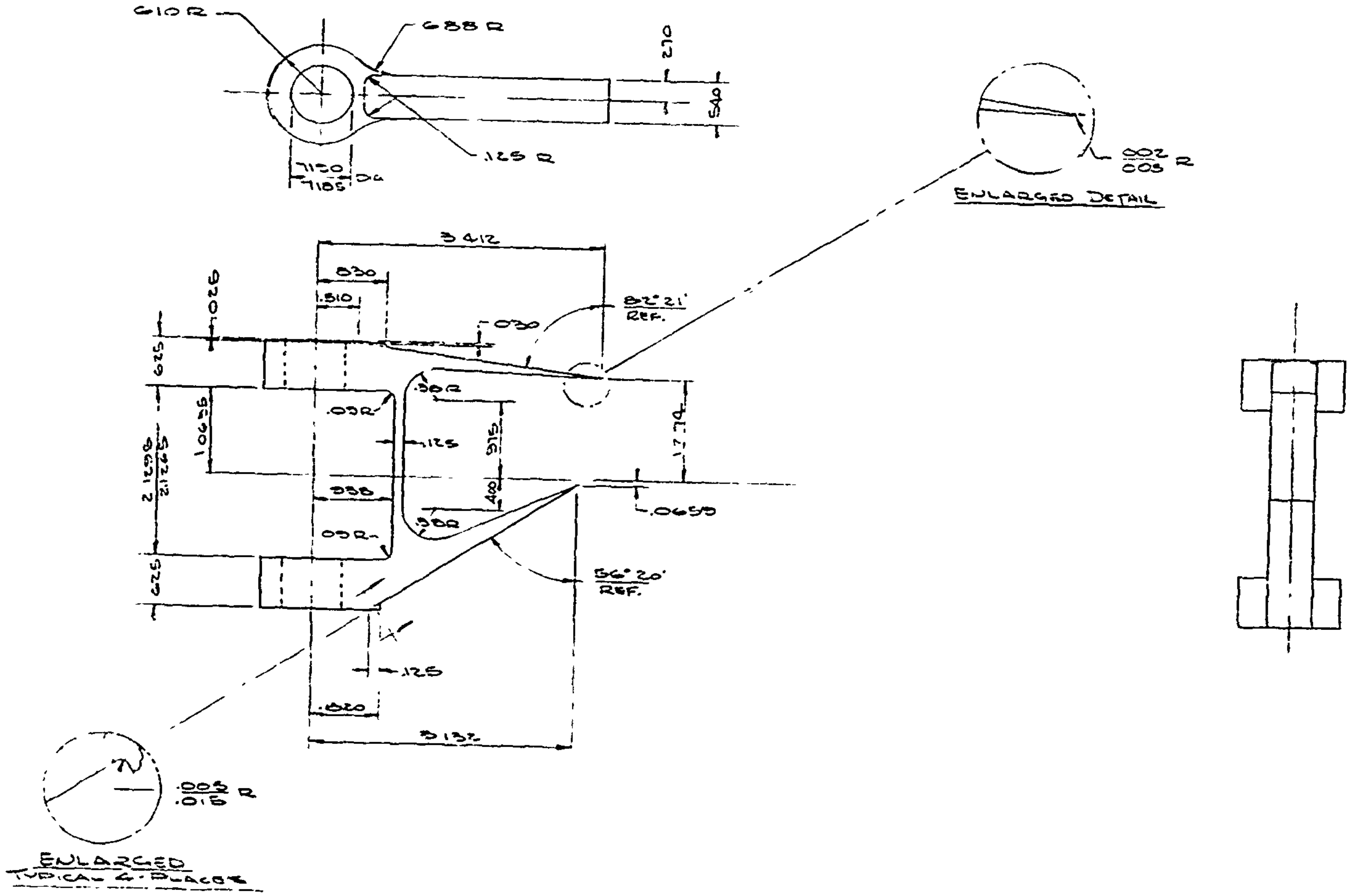
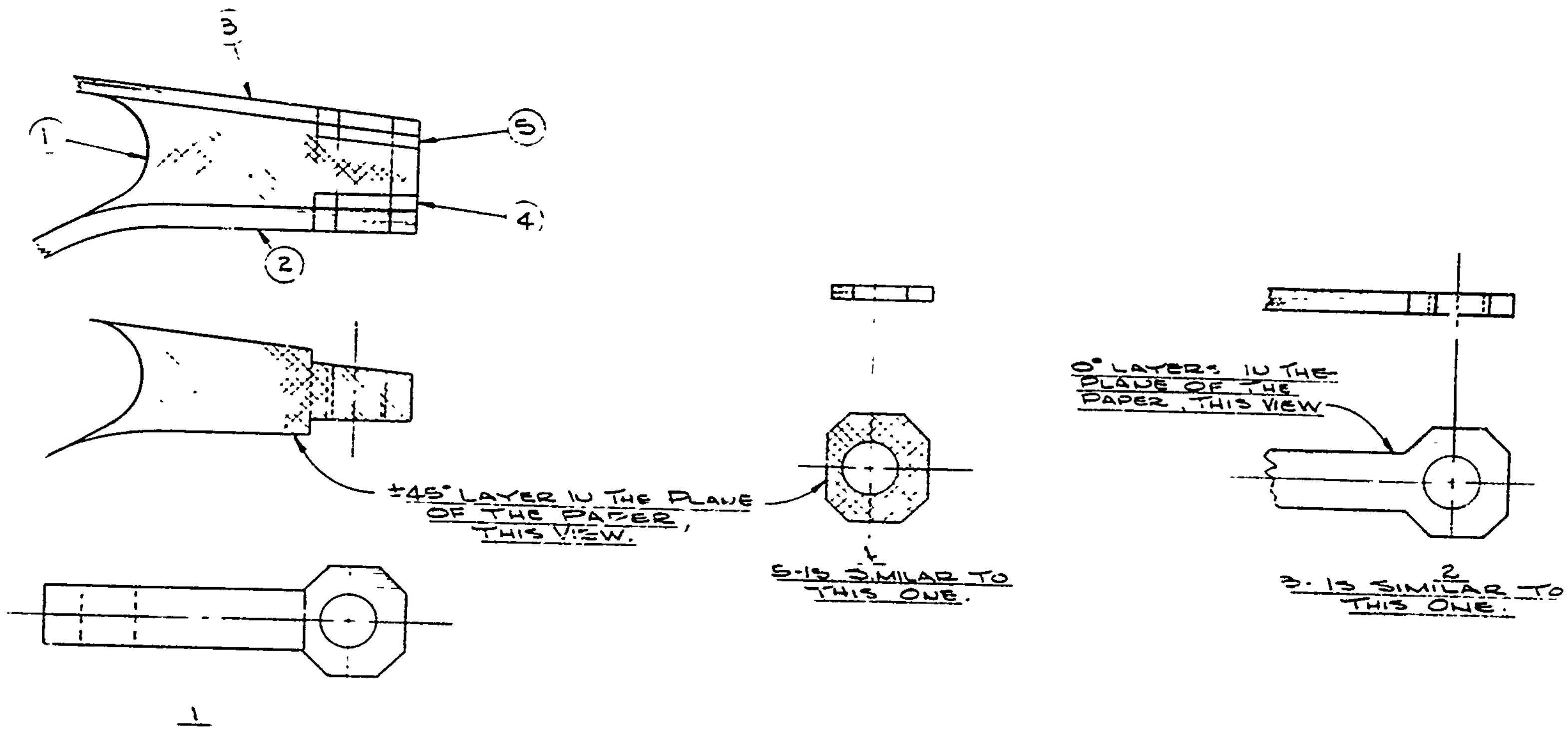



Figure 5-24. BORSIC-Aluminum Torque Arm Detail




REF. VXB-30971

Figure 5-25. BORSIC-Aluminum Torque Arm Details

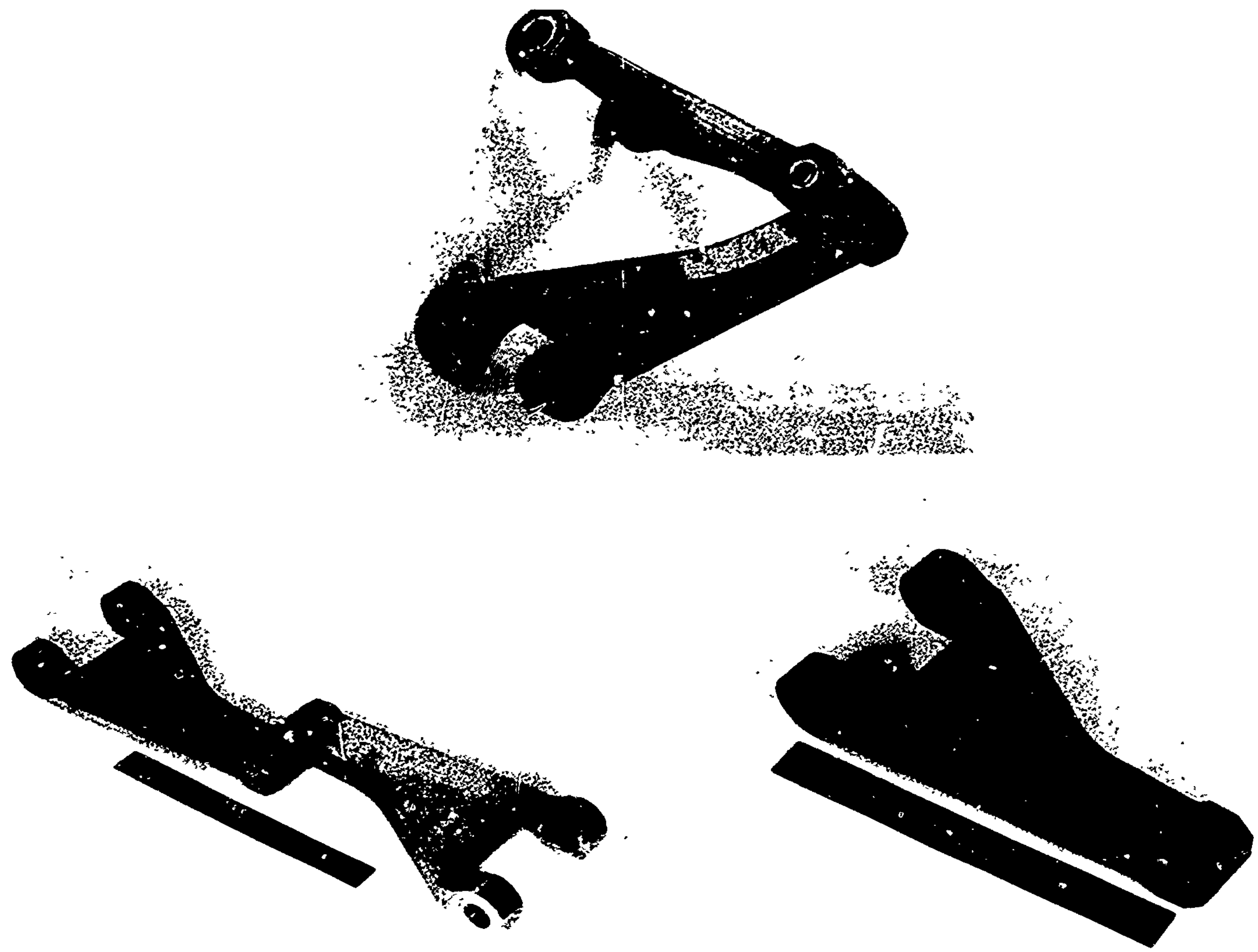
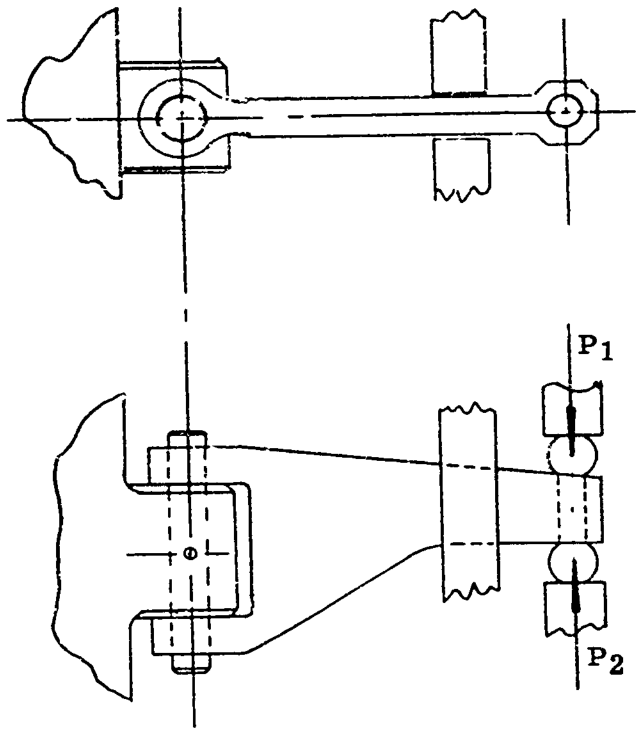


Figure 5-26. BORSIC-Aluminum Torque Arm Assemblies




Test Load Requirements

1. Load $P_1$ first. Load $P_1$ to 2250 Lbs. (1/2 limit)
2. Load $P_2$ to 3150 Lbs. (1/2 limit)
3. Load $P_1$ to 4450 Lbs. (limit)
4. Load $P_2$ to 6350 (limit)
5. Load $P_1$ to 6700 (ultimate)
6. Load $P_2$ to 9500 (ultimate)

Figure 5-27. BORSIC-Aluminum Torque Arm Structural Test Summary

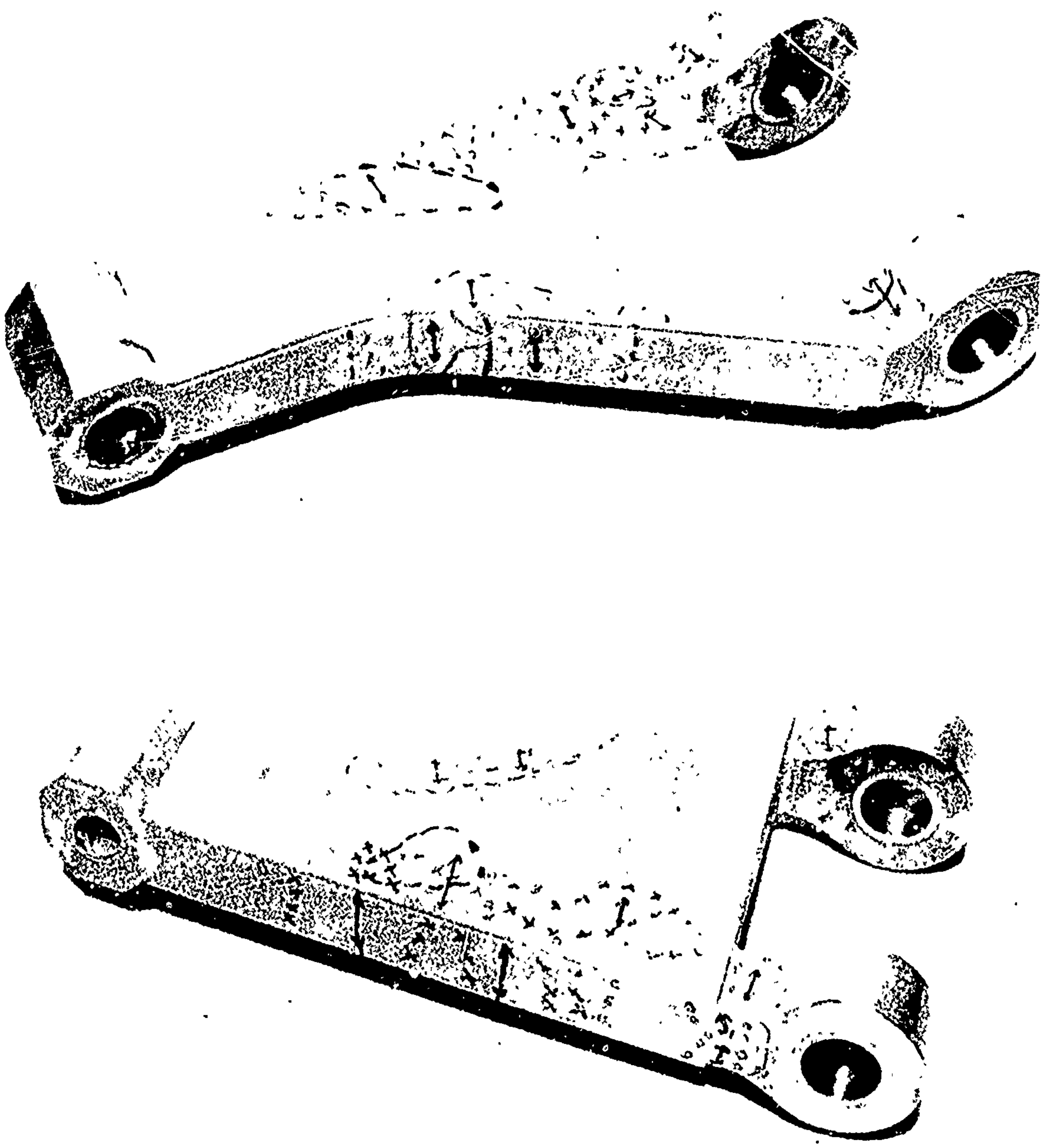


Figure 5-28. BORSIC-Aluminum Torque Arm with Brittle Lacquer

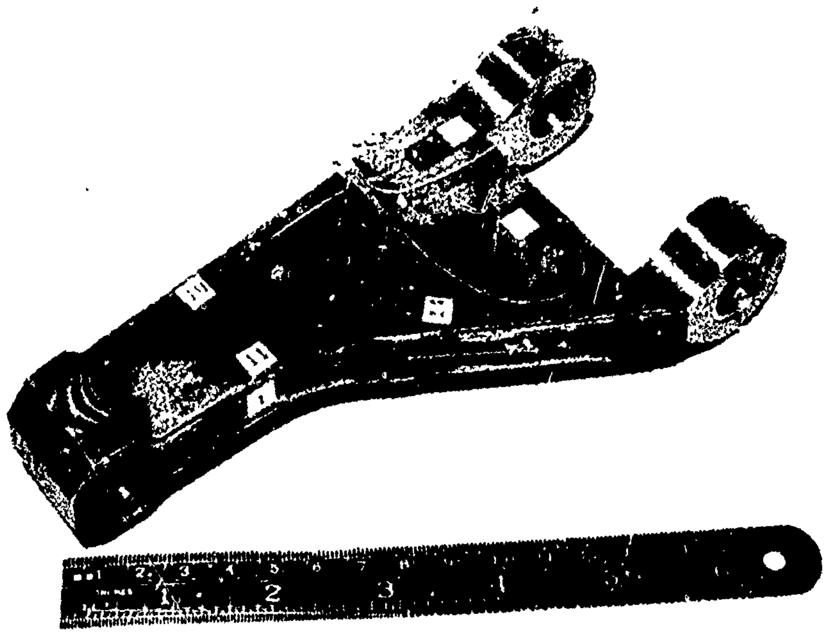


Figure 5-29. Strain Gaging of BORSIC-Aluminum Torque Arm

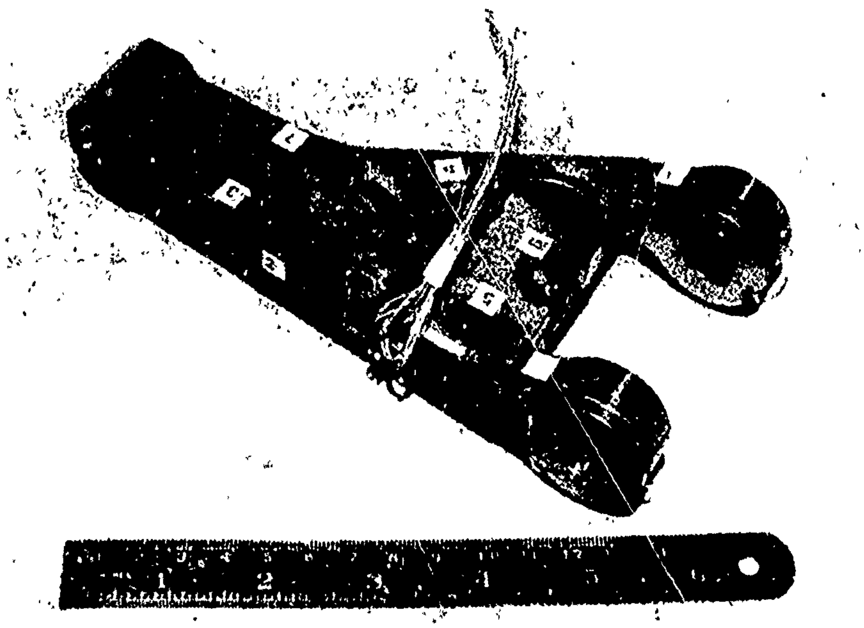


Figure 5-30. Strain Gaging of BORSIC-Aluminum Torque Arm

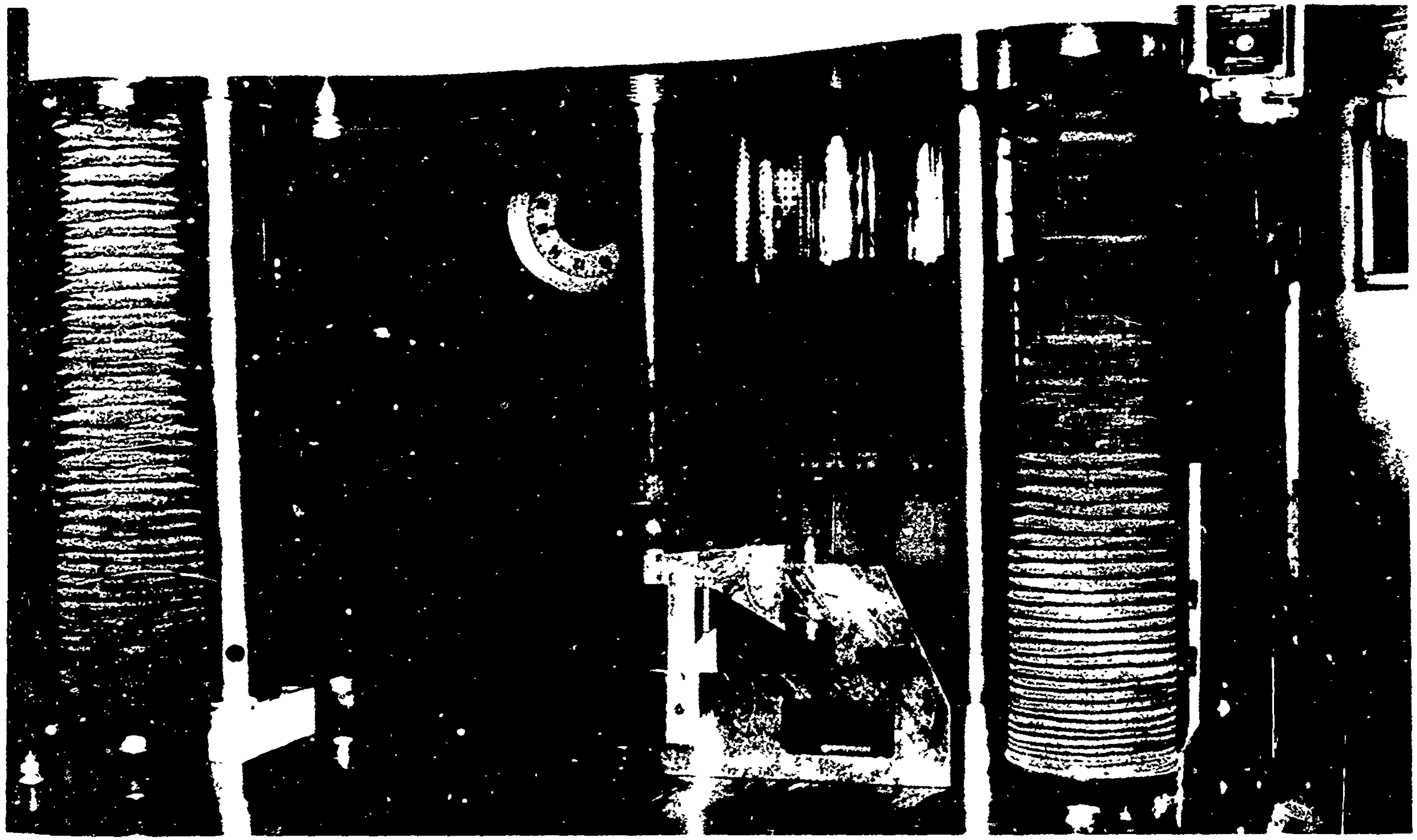


Figure 5-31. BORSIC-Aluminum Torque Arm Test Setup

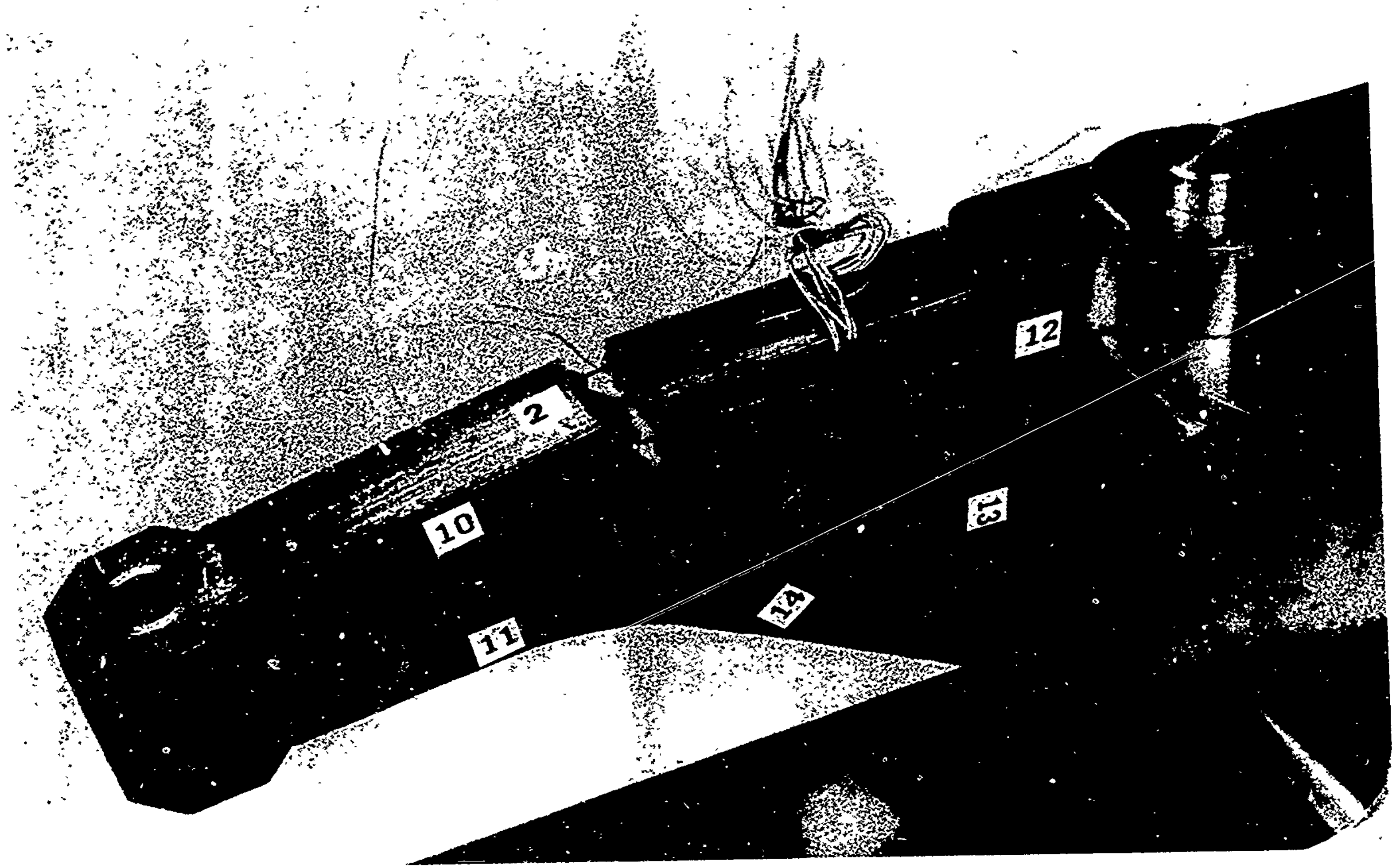
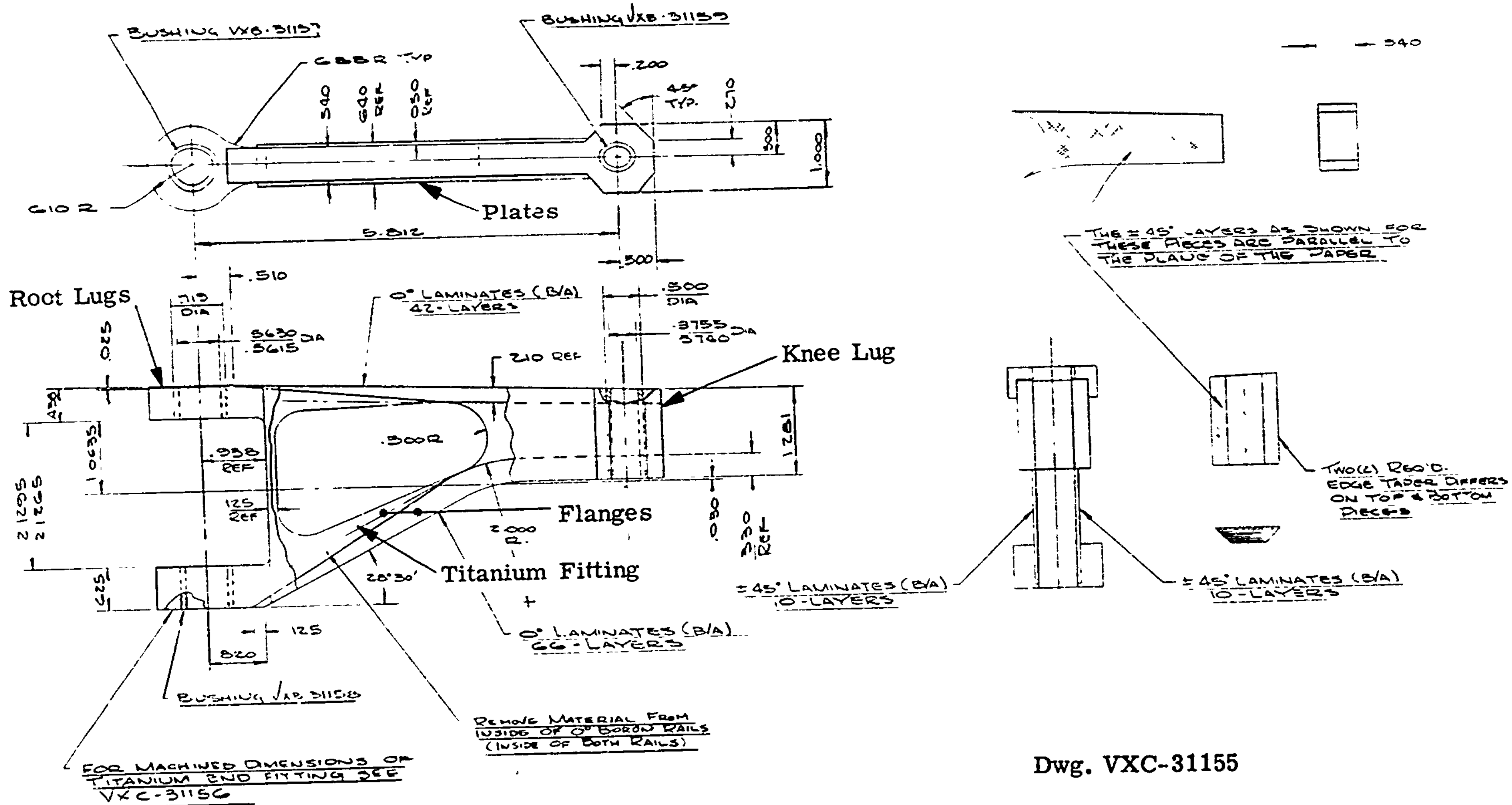



Figure 5-32. BORSIC-Aluminum Torque Arm Specimen




Dwg. VXC-31155

Figure 5-33. Torque Arm Assembly, BORSIC-Aluminum (Proposed Design)

### 5.2.1.3 BORSIC-Aluminum Outer Cylinder

The intended BORSIC-aluminum design is illustrated in Figure 5-34.

The basic component of this assembly is the boron composite cylinder. The wrap pattern varies from one end of the cylinder to the other to provide a more efficient construction with respect to the varying loading situation along the length of the cylinder. A chrome electrodeposited liner would be applied to the inner surface to provide leakage resistance and a hard sliding surface for the piston bearing.

The metal attachment fittings would be joined to the composite cylinder by aluminum brazing. The brazing cycle requires soaking at 1100-1130°F for approximately 1/2 hour. Type H-11 steel, heat treated to a strength level of 180 ksi UTS, was selected for the metal fittings since this grade of steel can sustain an 1150°F temperature without deterioration in strength. The cylinder OD would be machined to a taper of 0.10 inch per foot at the three locations to facilitate positioning and brazing of the steel fittings.

Some difficulties were encountered during the fabrication trials associated with production of the subscale cylinder specimens. This experience is detailed in Paragraph 8.1.5. Following is a summary of this problem.

At the initiation of this program fabrication experience by Hamilton Standard with respect to cylinder construction had been confined to a unidirectional laminate with filament layup oriented along the cylinder axis. The low shear strength of such a laminate pattern would require a heavy cylinder wall (approximately 0.600 inch) to withstand the torsion and shear loading imposed on this member.

The next concept to be considered involved a unidirectional boron composite cylinder overlayed on a titanium subcylinder, the purpose of the subcylinder being to support the shear generating portion of the load. This design also proved too heavy to be competitive.

At this point,Hamilton Standard agreed to investigate the feasibility of fabricating cylinders with 0°, ±45° and 90° fiber orientations. Using available tooling, a cone was fabricated from 0° and ±45° plies, and compaction of the cone wall was acceptable. The success of this fabrication trial initiated design work on the 0°, ±45° and 90° outer cylinder concept. The objective was to acquire an average layer thickness of 0.0048 inch during the compaction operation, but this too, was not sufficient. It was concluded that the layup pattern of 0°, ±45°, 90°, did not lend itself to be completely compacted in a closed system.

A recourse of this work was to modify the layup sequence in the cylinder to reflect fewer arrays with larger groups of fibers of the same orientation, and to increase the forming sequence to eight. This was aimed at cylinders suitable for piston applications. The new pattern defined by Bendix was 0° and 90°; however, this was modified slightly to permit a dispersion of the 90° laminae throughout the laminate thickness, rather than concentrate it at the outer surface. An examination of a cylinder with this array revealed lack of braze between some of the layup sequences.

The required development time, to perfect the process, made it impossible to fabricate cylinder.

### 5.1.2.4 BORSIC-Aluminum Piston

As discussed in Paragraph 5.2.1.3 process definition problems were encountered during fabrication trials to check out procedures for manufacturing suitable cylindrical products. Because of the inability to resolve these problems in time for Phase II hardware fabrication no specific piston designs were developed.

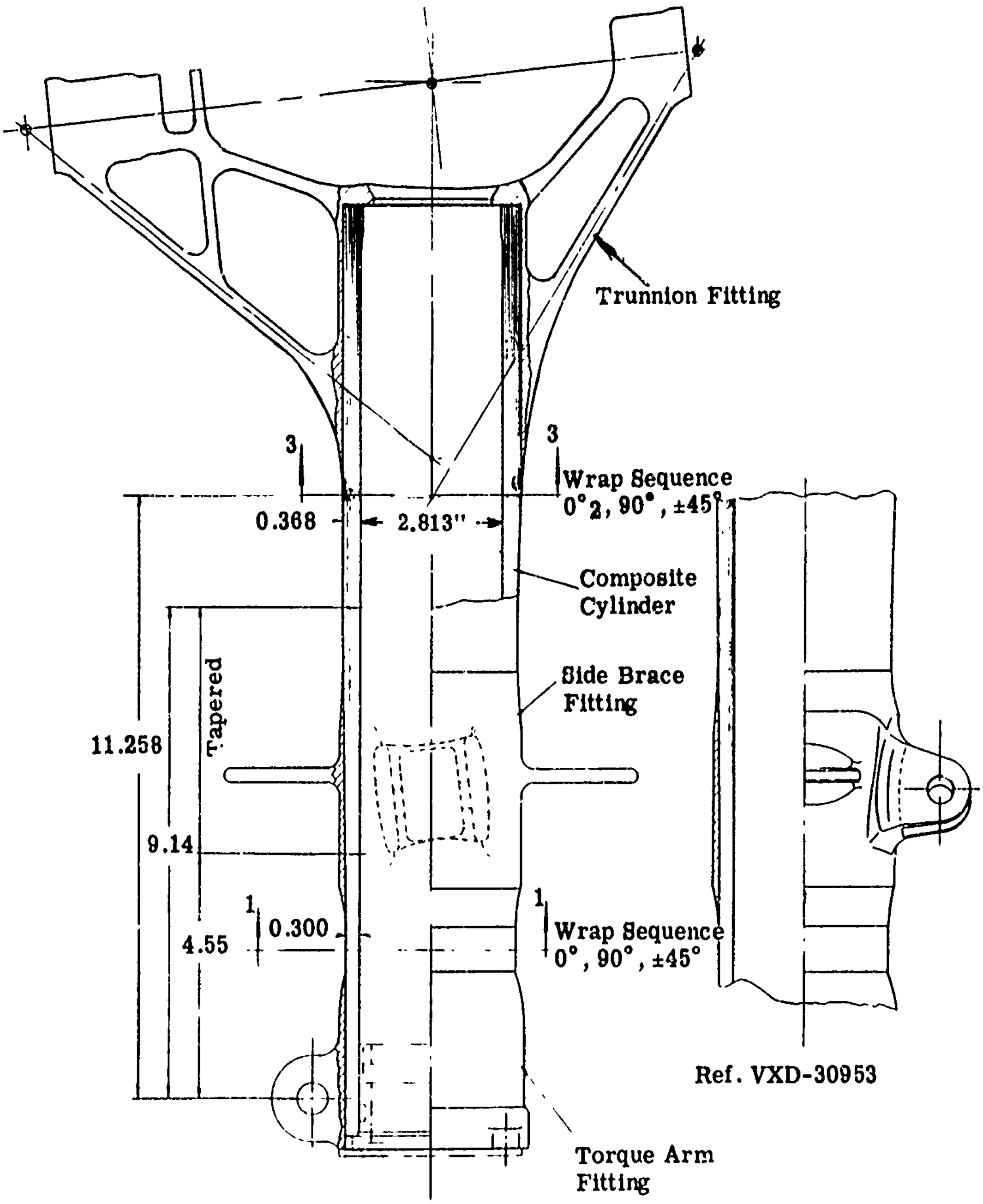



Figure 5-34. BORSIC-Aluminum Outer Cylinder (Proposed Design)

### 5.3.1 Boron-Epoxy Designs

This section describes the designs of prototype boron-epoxy landing gear components and the results of tests of specimens fabricated for design support trials. Material sources and fabrication and processing details are given in Paragraph 8-2.

#### 5.3.1.1 Boron-Epoxy Side Brace

The primary study effort was devoted to the prototype assembly shown in Figures 5-35 through 5-39.

Design Details - Prototype Assembly

The flanges of the individual links are formed by a continuously wound boron filament strap, the filaments being oriented in the axial direction. The flanges are stabilized by an aluminum honeycomb core cemented between the flanges.

The strap is retained at the ends by grooved recesses machined into the aluminum end fittings. This end fitting design provides positive retention of the strap and the ability to support compression loading. The strap is cushioned within the retaining groove by a urethane filler to prevent fretting and to alleviate local concentrations of bearing and shear stresses.

This concept proved very successful during the trial specimen fabrication and structural tests described below.

Fabrication and Test Details - Prototype Assembly

One assembly of the design shown in Figure 5-35 was fabricated and structurally tested. The fabrication details are given in Paragraph 8.2.3.2 and the test results are described in Paragraph 7.2.2.2.

Fabrication and Test - Trial Specimen

During the design phase, the trial specimen shown in Figures 5-40 and 5-41 was fabricated as a check on the structural integrity of the concept shown in Figures 5-36 and 5-37. The details of fabrication are described in Paragraph 8.2.3.1. The resulting parts are shown in Figures 5-42 and 5-43. The test results are described below.

A summary of the axial loads which were specified for the structural test of this specimen is given below. The purpose of the test was to achieve the same load level as the design loads given in Table 4-2.

| Step | Load, lbs. |
|---|---|
| 1 | 5,000 T |
| 2 | 5,000 C |
| 3 | 10,000 C |
| 4 | 9,200 T (Lim.) |
| 5 | 20,000 C (Lim.) |
| 6 | 30,000 C (Ult.) |

T = tension
C = compression
Lim. = design limit
Ult. = design ultimate

The test setup is shown in Figure 5-44. The specimen successfully passed the test loads through Step 5. During application of Step 6 the specimen failed at a compression load of 25,700 pounds, or 86 percent of the target ultimate load of 30,000 pounds. Failure was by shearout of one of the aluminum end fittings, Figure 5-45. The boron-epoxy filament wound strap remained intact and visual inspection did not reveal any damage to this part.

Since the failed end fitting was still capable of applying a tension load, the specimen was returned to the loading device for a tension test. The specimen sustained a load 7,750 pounds when failure occurred in the filament strap, in the circular portion, at the end corresponding to the failed fitting. This load was less than the tension load of 9,200 pounds sustained previously in Step 4. It was concluded from this that the filament straps were damaged during the previous compression loading.

The thickness of the retaining flanges of the prototype fittings, Figure 5-36, was increased to improve the shear out strength.

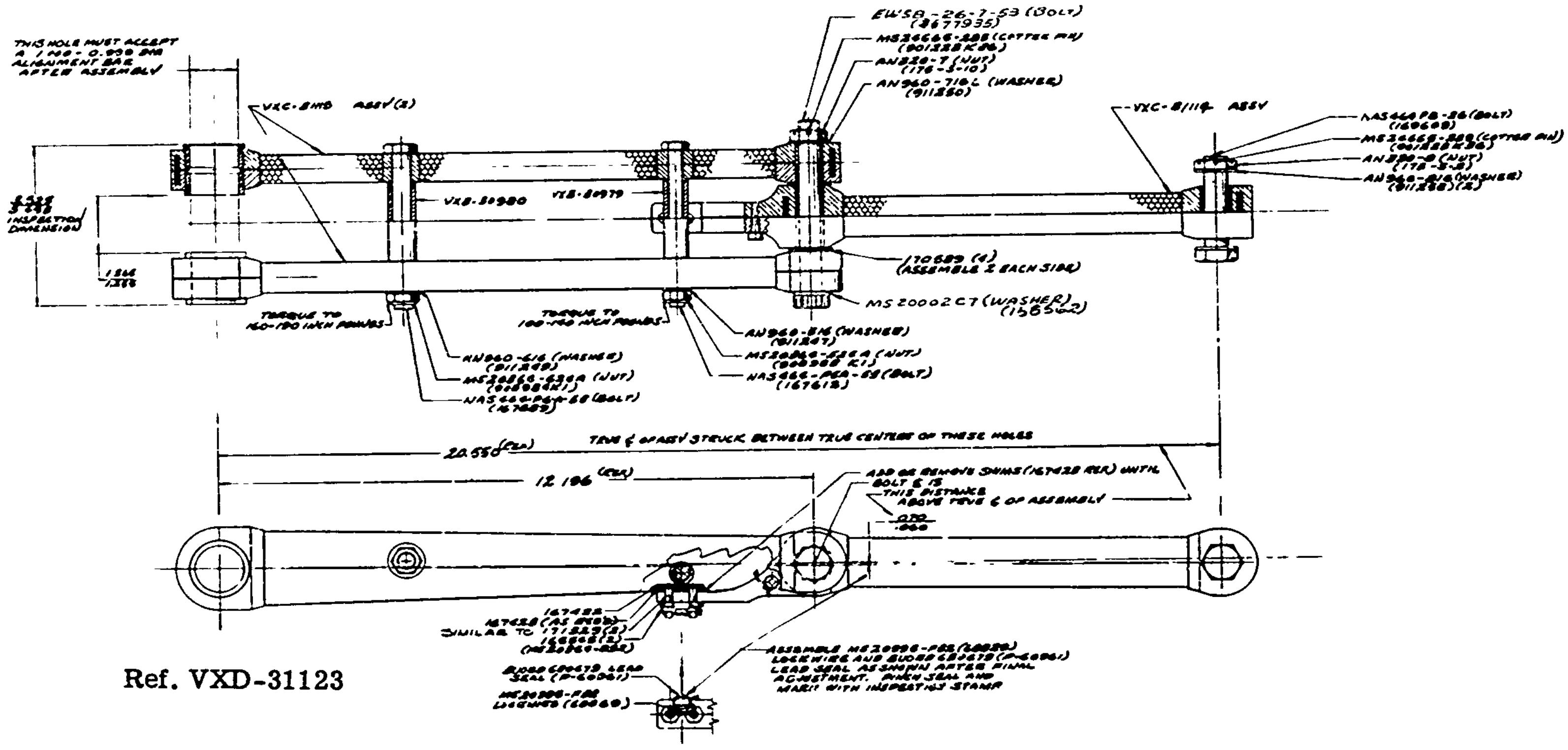
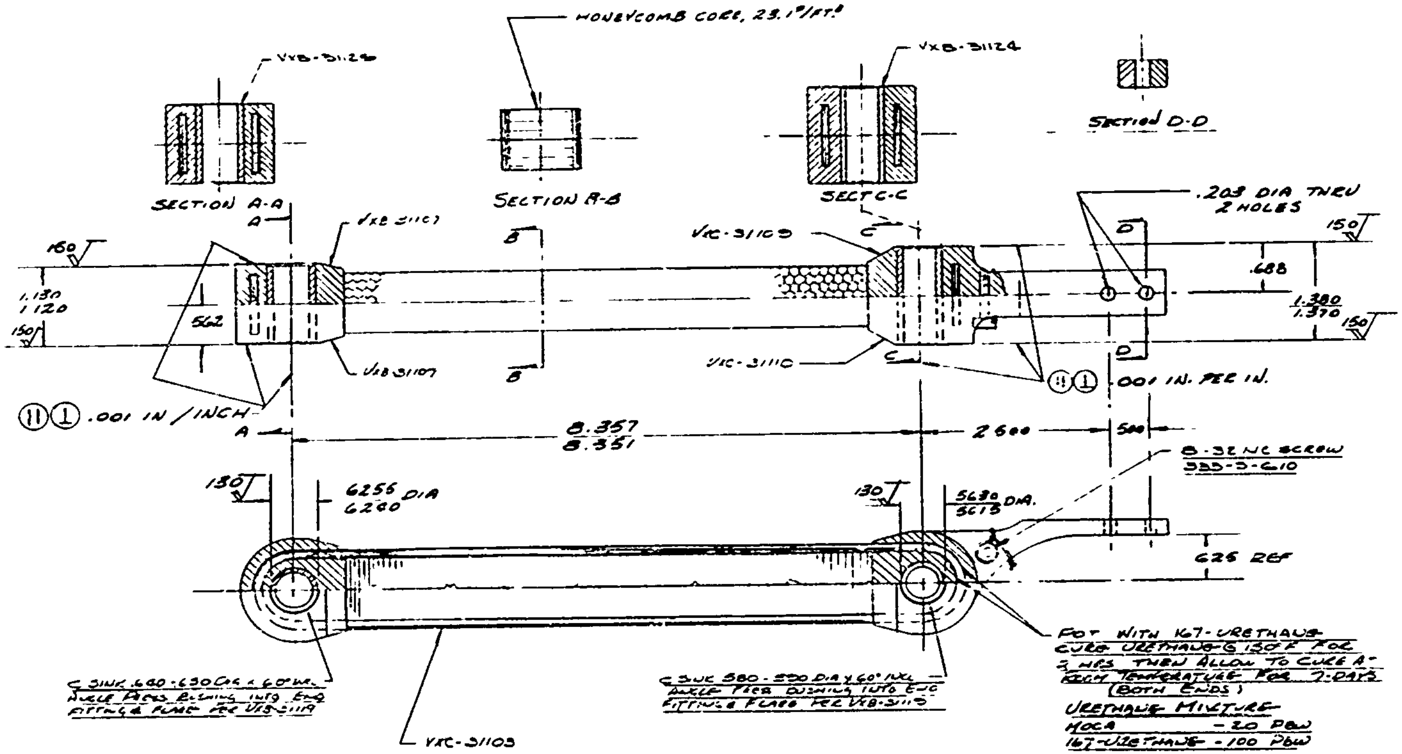
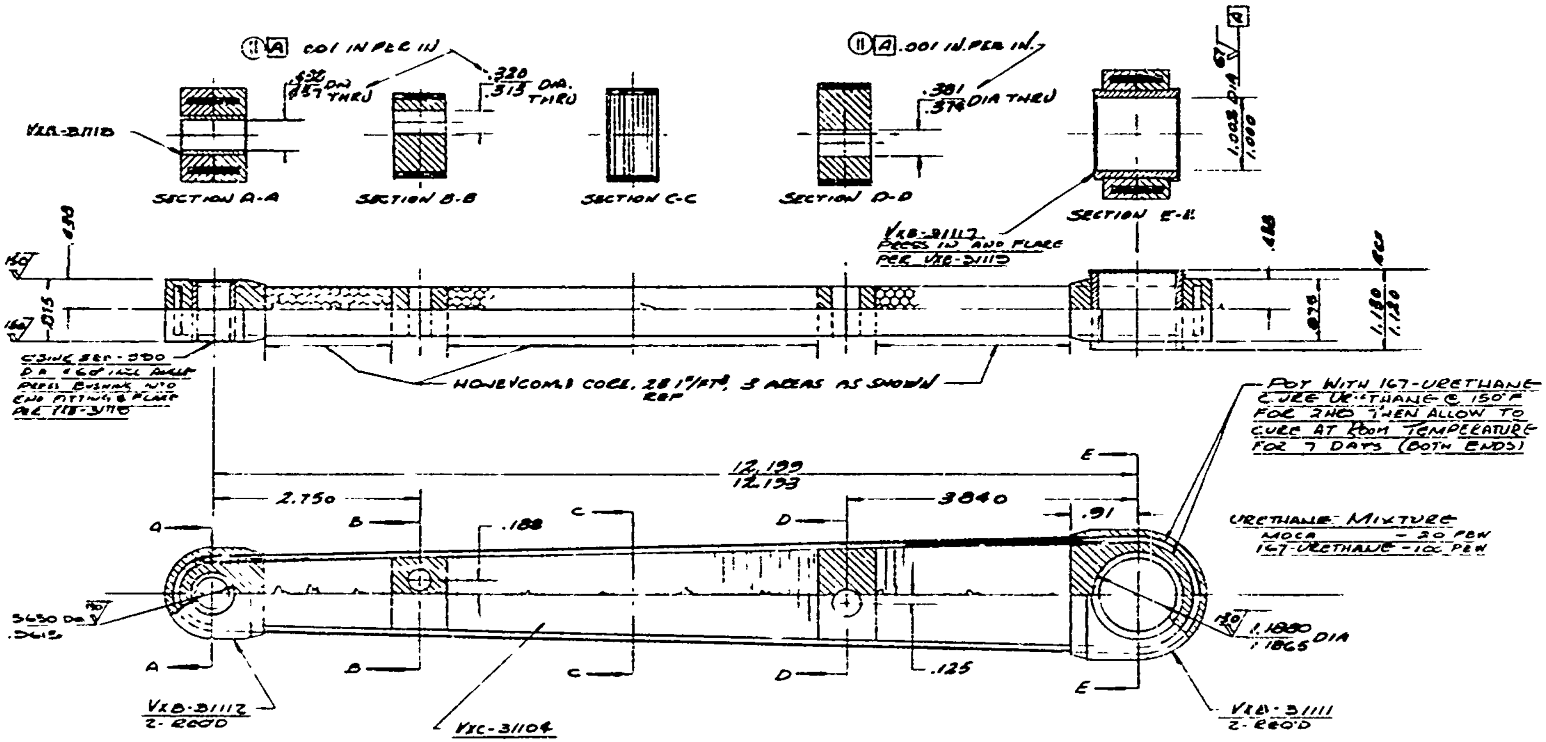



Figure 5-35. Side Brace Assembly, Boron-Epoxy (Proposed Design)



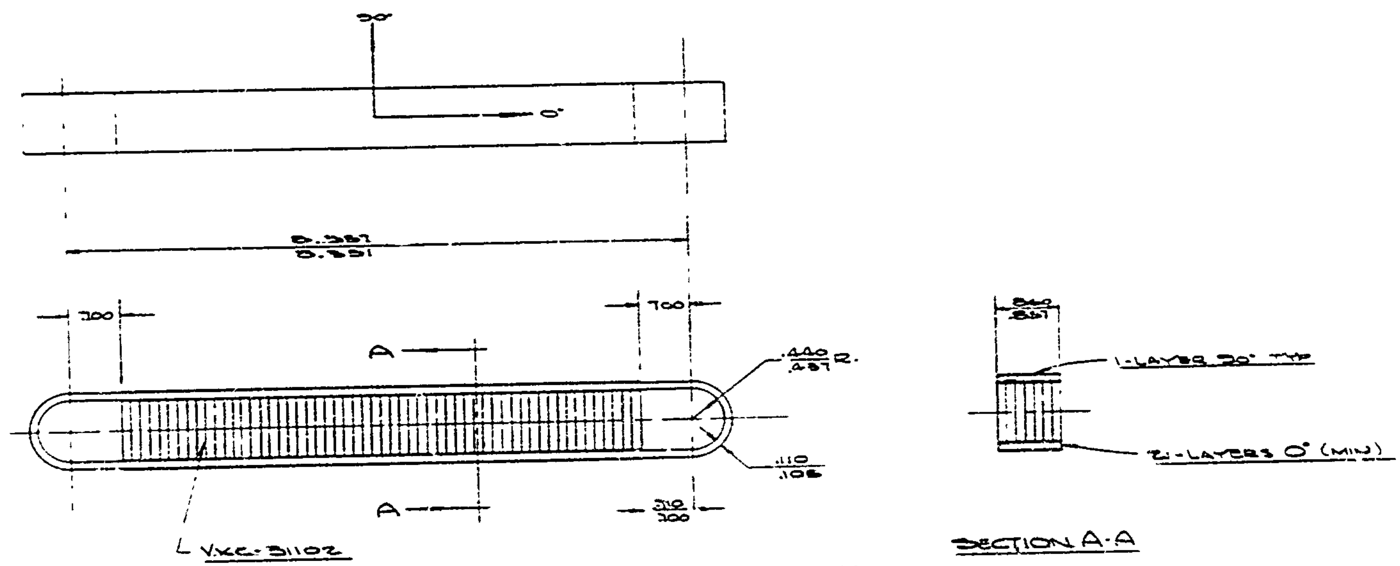

Ref. VXC-31114

Figure 5-36. Side Brace Lower Link, Boron-Epoxy (Proposed Design)



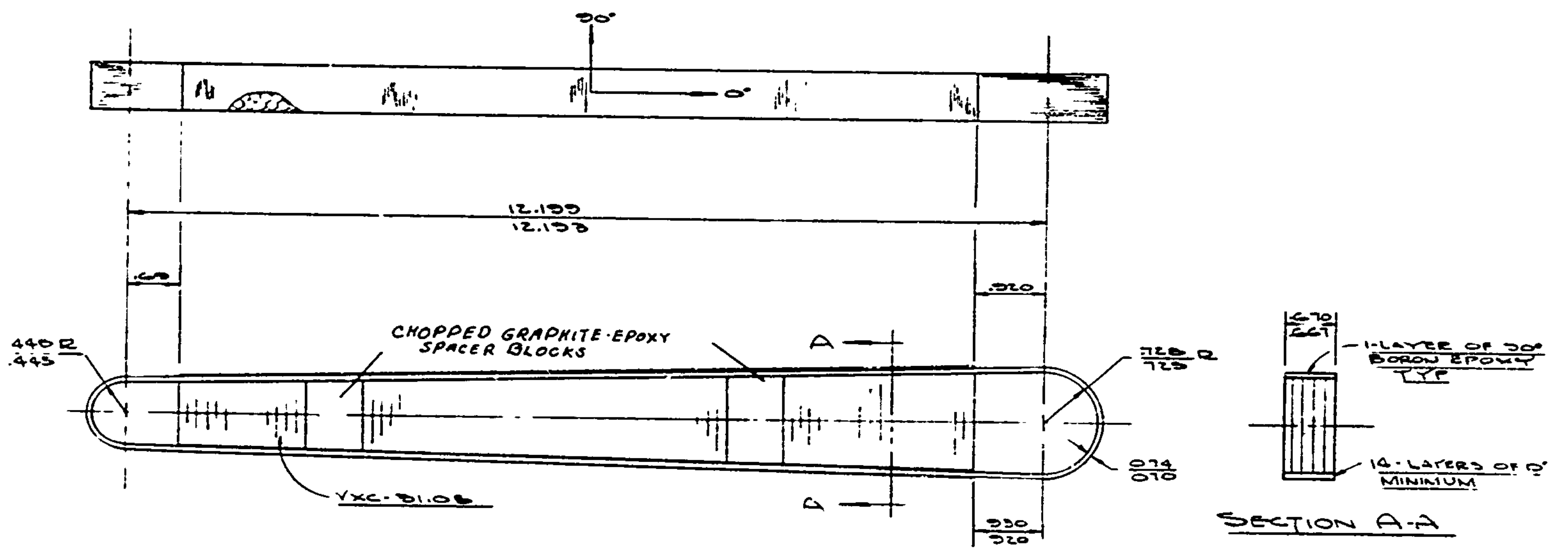

DWG. VXC-31115

Figure 5-37. Side Brace Upper Link, Boron-Epoxy (Proposed Design)



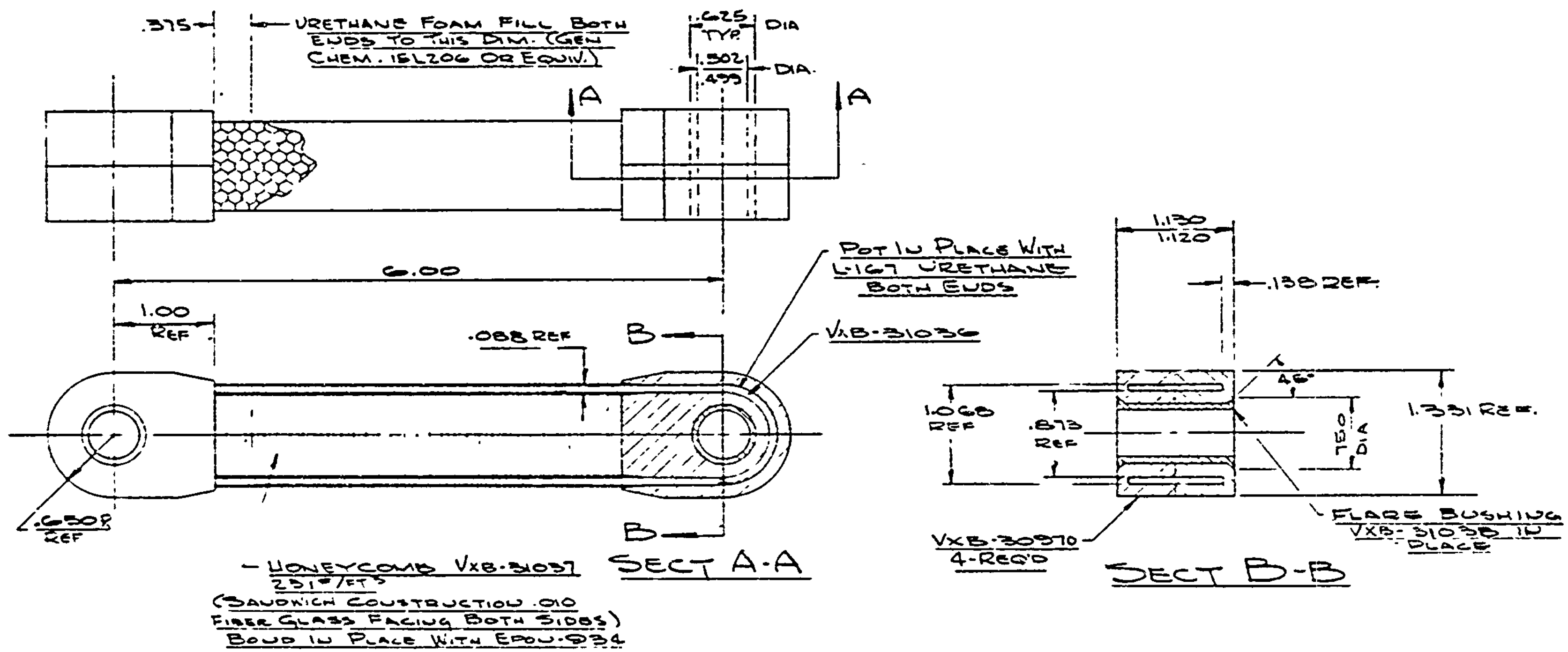

Ref. VXC-31103

Figure 5-38. Side Brace Flange Assembly - Lower Link



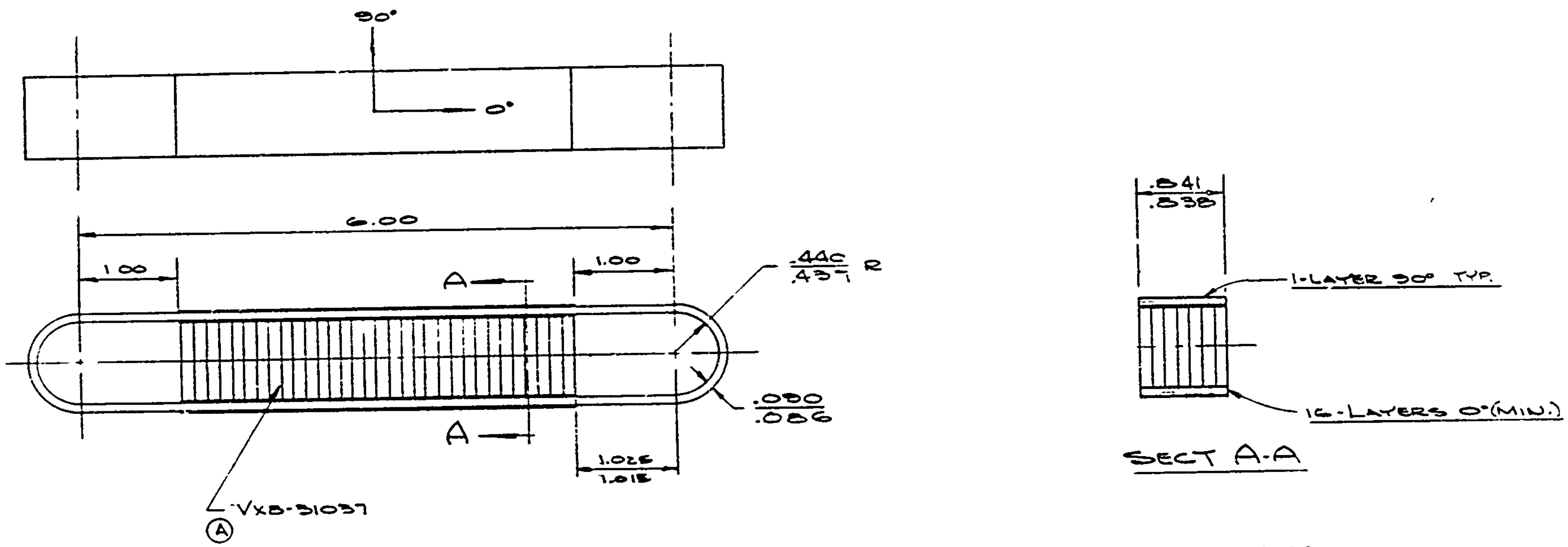

Ref. VXC-31104

Figure 5-39. Side Brace Flange Assembly - Upper Link




Ref. VXB-30985

Figure 5-40. Boron-Epoxy Side Brace Specimen




REF. VXB-31036

Figure 5-41. Side Brace Flange Assembly - Trial Specimen

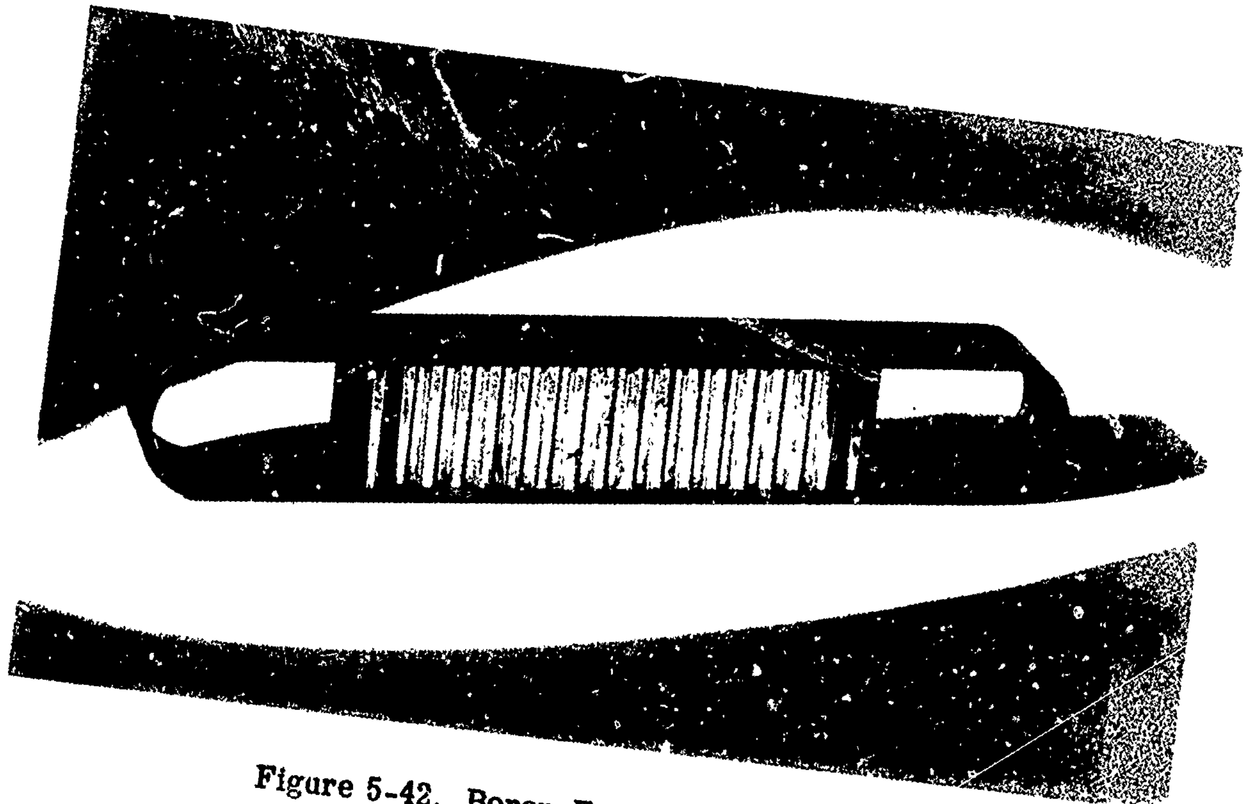


Figure 5-42. Boron-Epoxy Side Brace Specimen

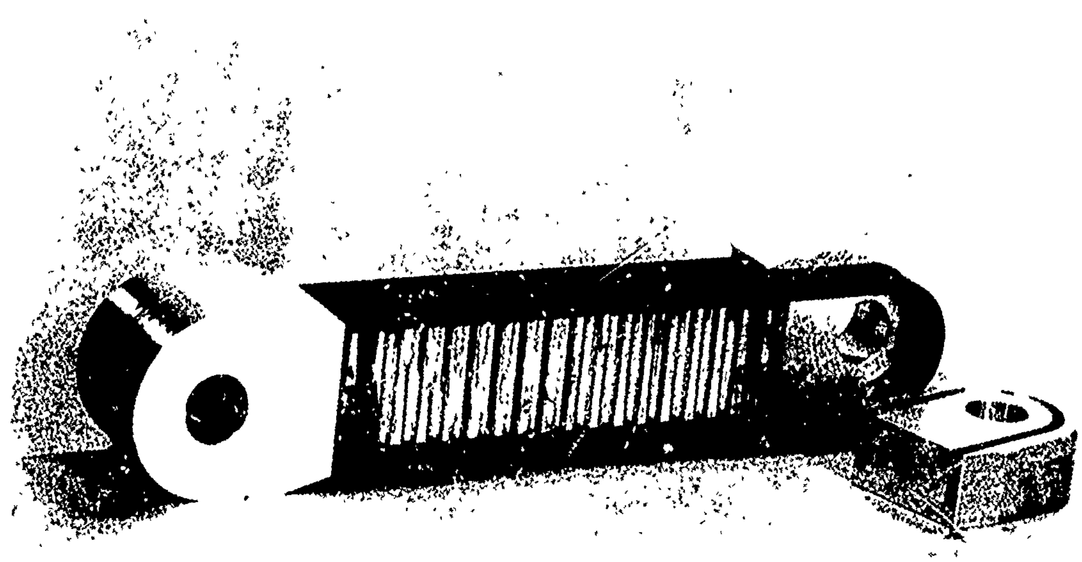


Figure 5-43. Boron-Epoxy Side Brace Specimen

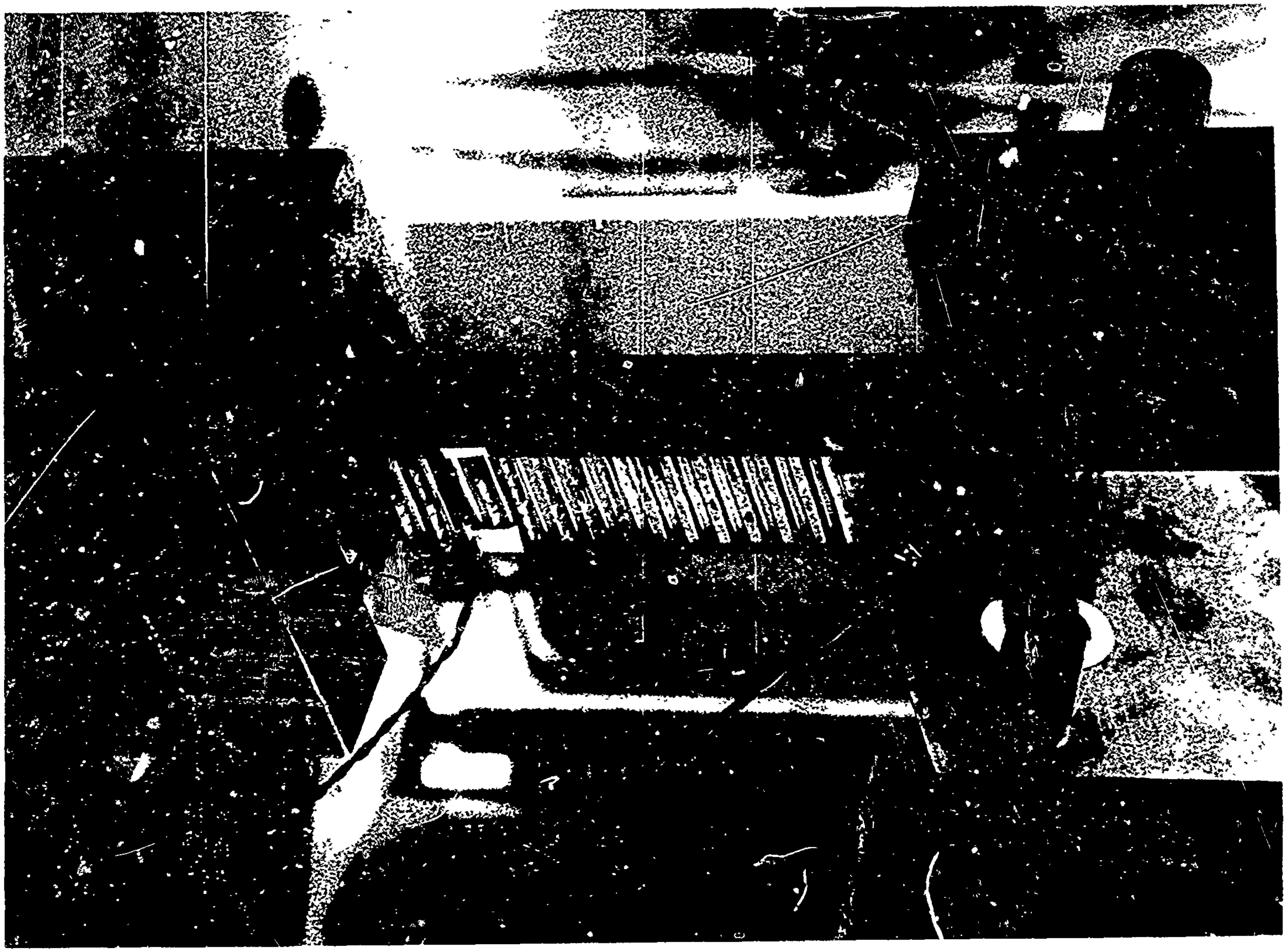


Figure 5-44. Boron-Epoxy Side Brace Specimen in Loading Rig

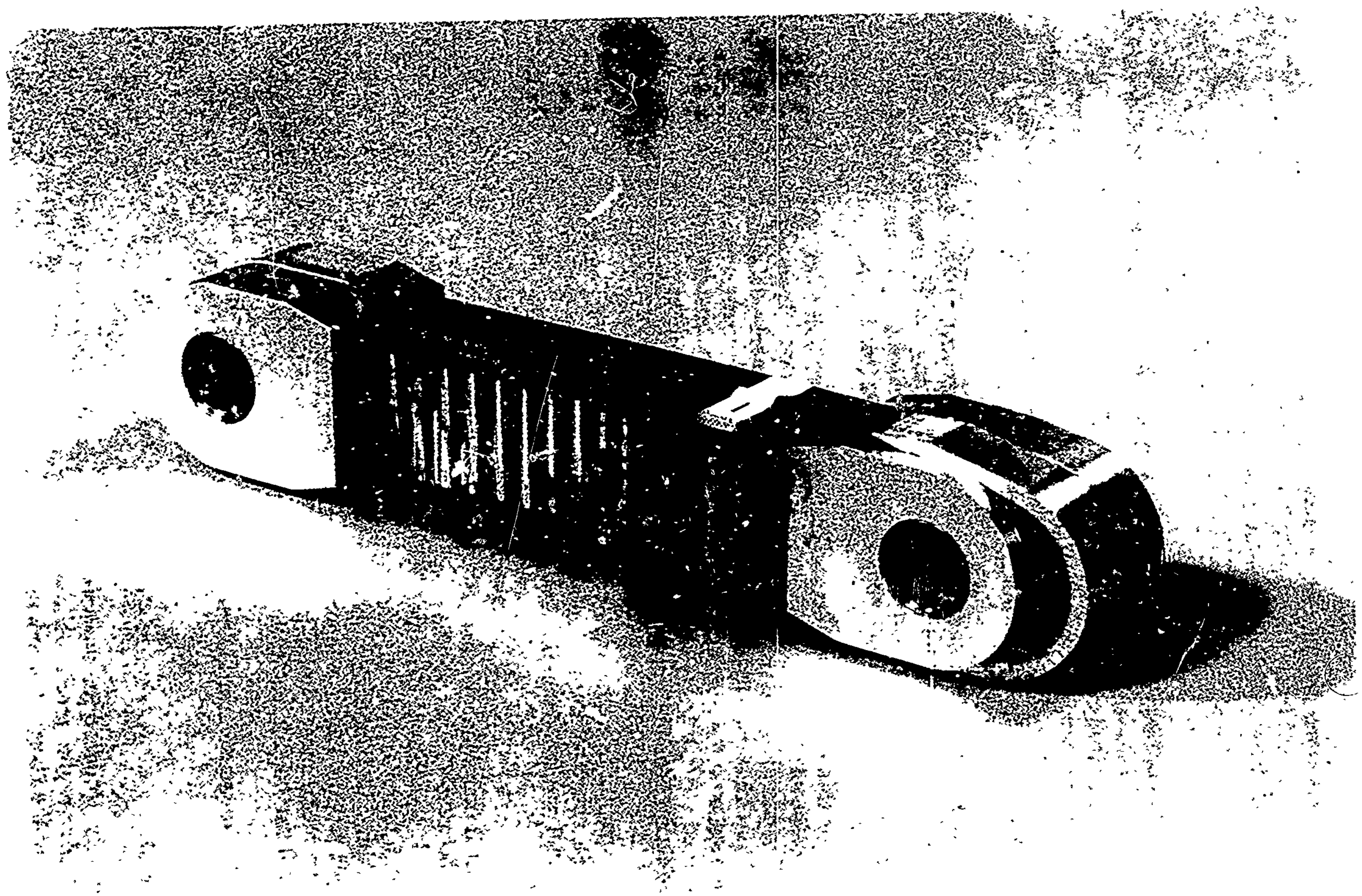


Figure 5-45. Failed Boron-Epoxy Side Brace Specimen

### 5.3.1.2 Boron-Epoxy Torque Arm

Two design concepts were considered in detail. A trial specimen of the first design was fabricated and structurally tested. Due to bonding difficulties and excessive weight, it was abandoned in favor of a second design. These are discussed below.

#### First Design

Figure 5-46 shows the first boron-epoxy torque arm design given serious consideration. It consists of unidirectional boron filament flanges joined at the knee end by a bonded steel insert and stabilized by ±45° boron filament side plates bonded to the flanges. The root and knee ends are reinforced by a graphite filament band to provide for transfer of shear from one flange to the other. The lug holes are strengthened by use of spiral wound reinforcements (spiral doilies or wafers).

A trial specimen of this design was fabricated and structurally tested during Phase I to check out fabrication techniques and structural integrity. A description of the fabrication details is given in Paragraph 8.2.4.1. The fabricated torque arm is illustrated in Figures 5-47 and 5-48. The test results are summarized below.

The test setup for this specimen is shown in Figures 5-49 and 5-50. A summary of the test loadings is shown in Figure 5-51. The column labelled "Required" indicates the specified loading which parallels the design load requirements indicated by $Y_k$ in Table 4-1. This column also indicates the sequence in which the loads were to be applied. However, due to a misinterpretation of the test instructions, the directions of $P_1$ and $P_2$ were reversed and the loads were applied instead in the magnitudes and sequence listed in the column headed "Applied."

The torque arm ruptured in the knee region while applying 6000 pound load in the $P_1$ direction. The strength of the torque arm was indicated by the test to be greater than 47 percent of design ultimate in the $P_2$ direction and 90 percent of design ultimate in the $P_1$ direction.

This design failed somewhat prematurely in structural test because of an imperfect bond which existed between the metal insert and the boron composite surfaces, Figures 5-52, 5-53 and 5-54. It is believed that the target load could be achieved with a sound bond line. The design is nevertheless somewhat of a disappointment. The knee lug design proved to be a difficult fabrication problem with respect to achieving a good bond between the metal insert and the boron composite flanges. In addition the design is somewhat heavy due to the metal insert in the knee joint. The insert is necessary however to carry the high shear bond intensity in this region.

It is believed that these difficulties can be overcome with the finally proposed design discussed next.

#### Second Design

The concept finally proposed for the boron-epoxy torque arm is shown in Figure 5-55. The primary load carrying members are the flanges which consist of filaments oriented along the length of the flange, the primary load path. The flanges are tied together by

$\pm 45°$ crossply side plates which stabilize the flanges and promote shear flow between them. Load transfer between root lugs is promoted by graphite filament band wound around the entire box section at that end. Graphite filament was selected for this purpose because of the small radii which occur at the flange corners.

The pin holes at the root end of the flanges are reinforced by spiral wound layups. The high intensity shear flow between the flanges at the knee lug is resisted by the transversely disposed crossply shear plates.

It may be noted that, except for the steel bushings, this proposed torque arm configuration would be constructed entirely from filament composite materials.

A summary of the proposed fabrication procedure for this design is given in Paragraph 8.2.4.2.

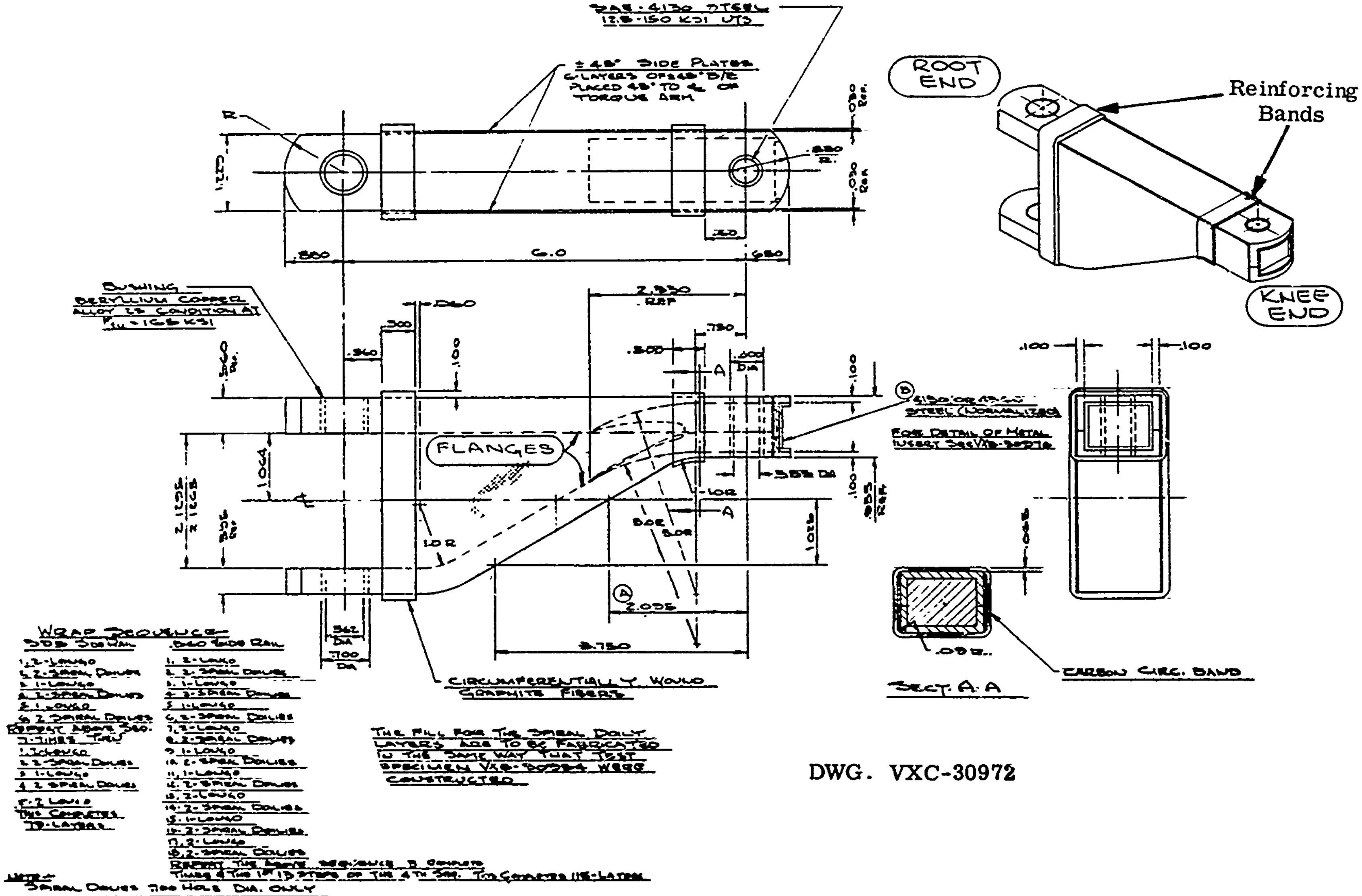



Figure 5-46. Boron-Epoxy Torque Arm Specimen

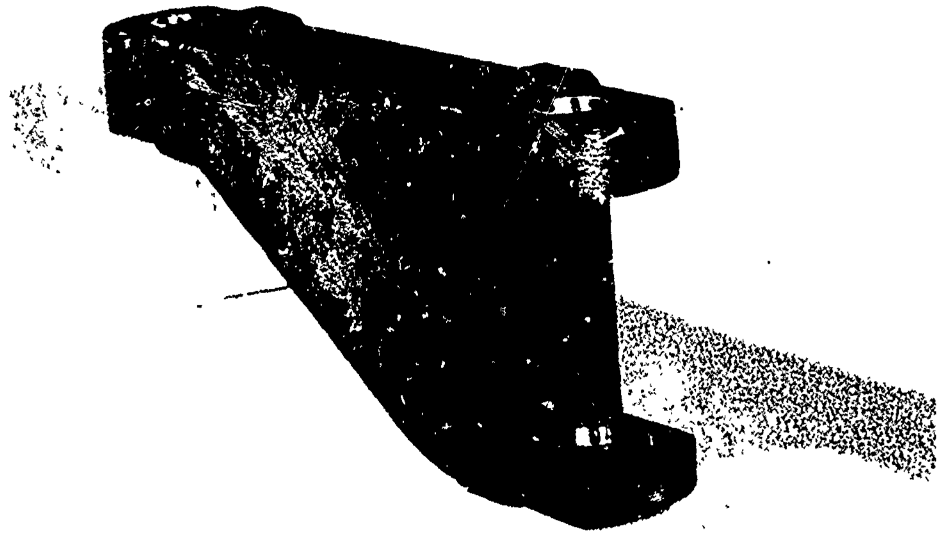


Figure 5-47. Boron-Epoxy Torque Arm Specimen

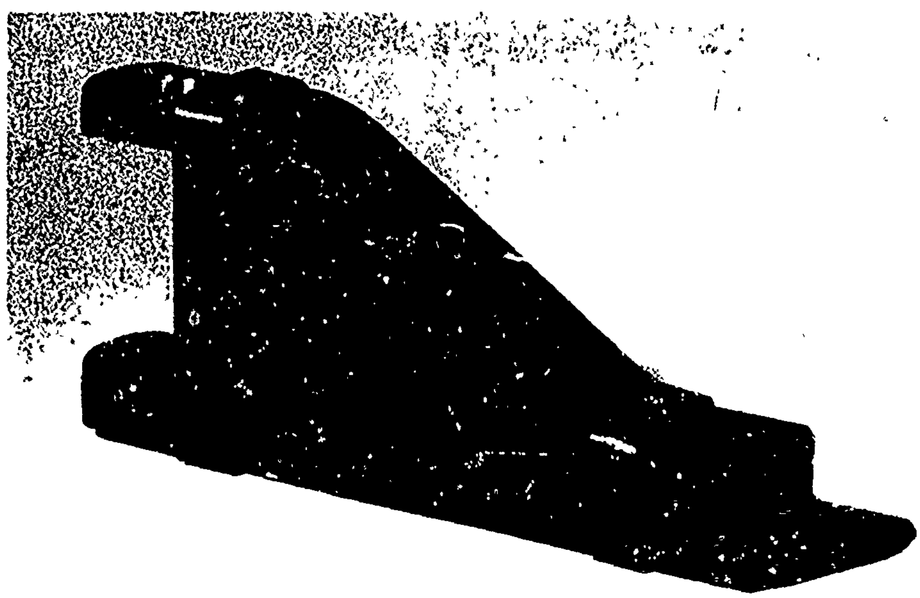


Figure 5-48. Boron-Epoxy Torque Arm Specimen

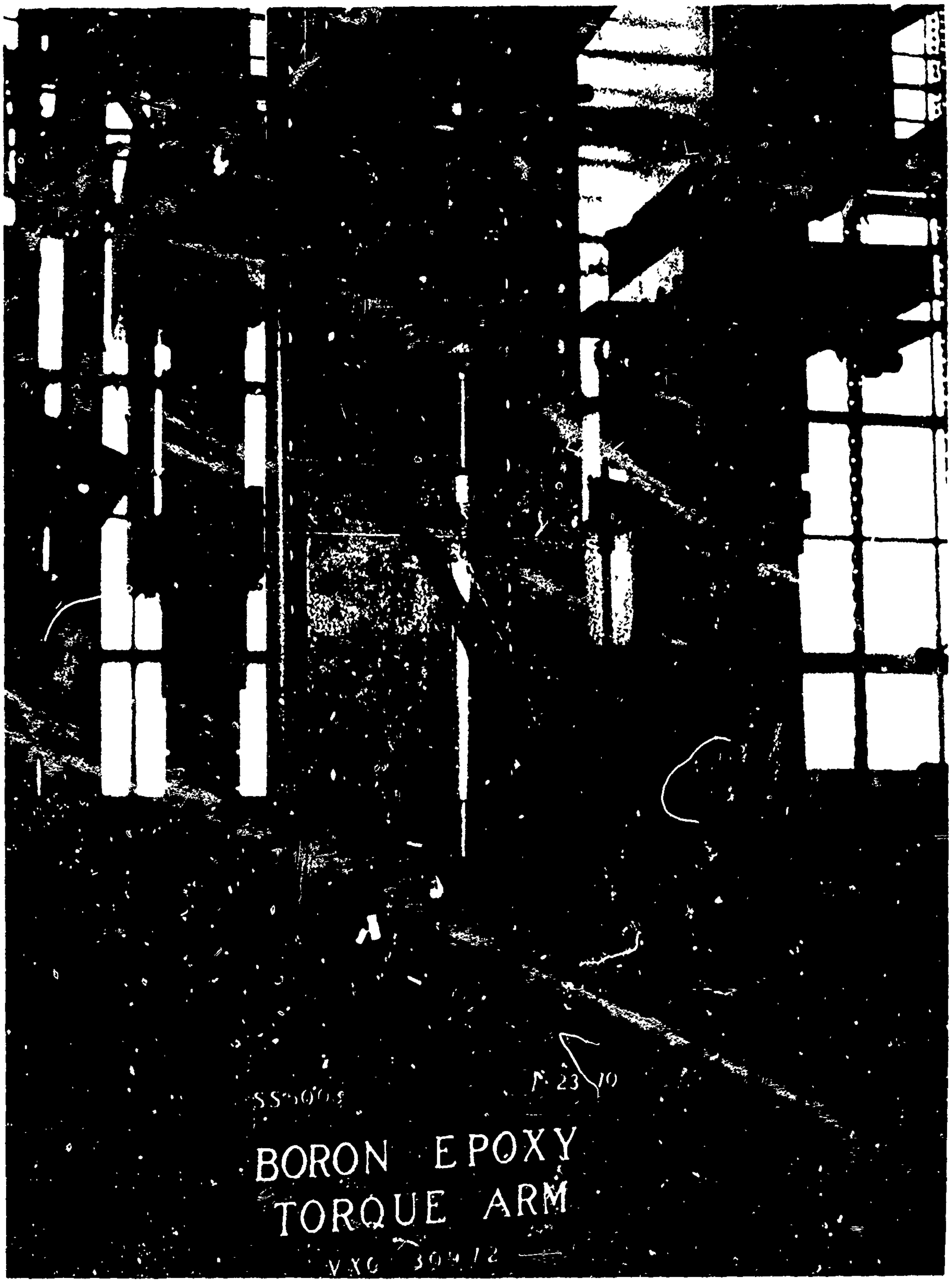



Figure 5-49. Boron-Epoxy Torque Arm Specimen Test Setup

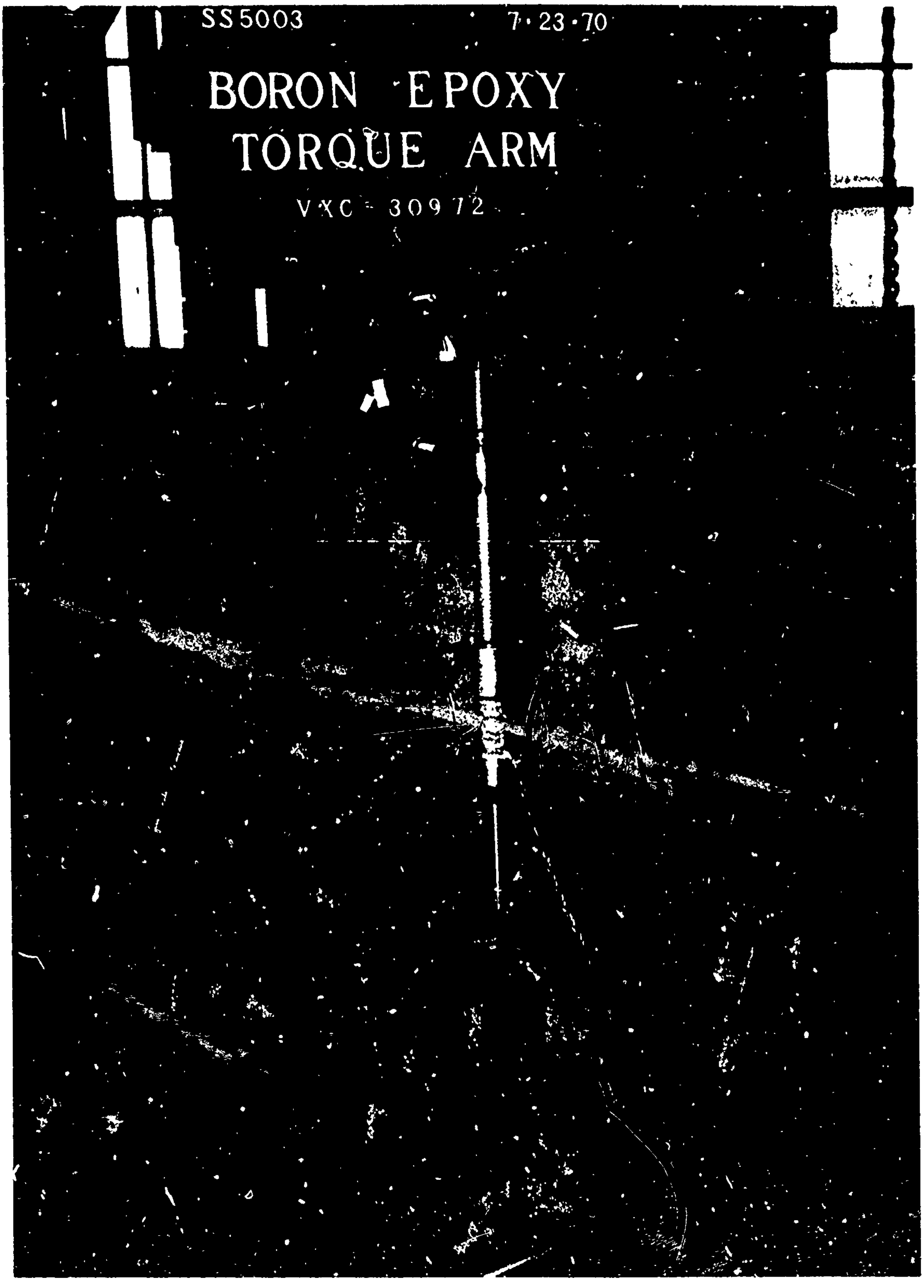
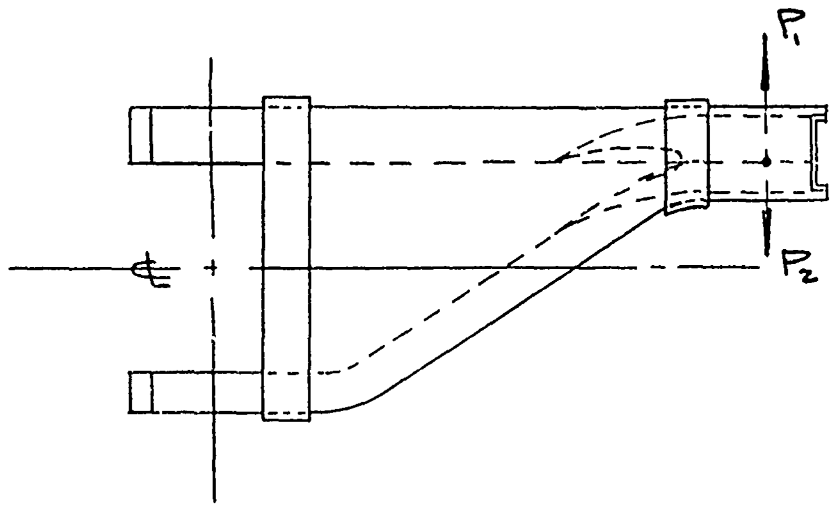



Figure 5-50. Boron-Epoxy Torque Arm Specimen Test Setup




| Load Direction | Required | | | Applied | |
|---|---|---|---|---|---|
| | Level | Load | Sequence | Load | Sequence |
| $P_1$ | 1/2 Limit | 2250 | 1 | 3150 | 2 |
| | Limit | 4450 | 3 | 6000 | 4 |
| | Ultimate | 6700 | 5 | | |
| $P_2$ | 1/2 Limit | 3150 | 2 | 2250 | 1 |
| | Limit | 6350 | 4 | 4450 | 3 |
| | Ultimate | 9500 | 6 | | |

Indicated Strength

$P_1 = 6000/6700 = 0.90$ Ultimate

$P_2 > 4450/9500 = 0.47$ Ultimate

Figure 5-51. Test Load Summary for Boron-Epoxy Torque Arm Specimen

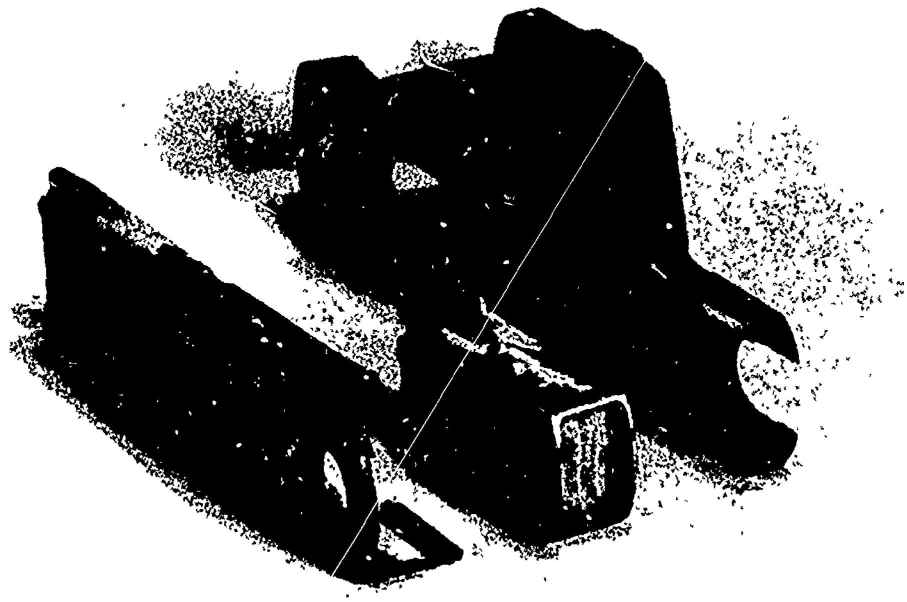


Figure 5-52. Failed Boron-Epoxy Torque Arm Specimen

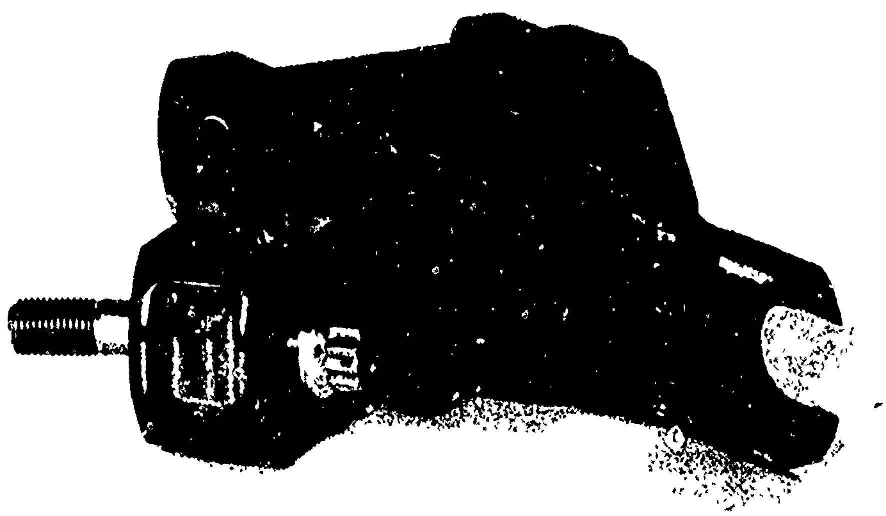


Figure 5-53. Failed Boron-Epoxy Torque Arm Specimen

Figure 5-54. Failed Boron-Epoxy Torque Arm Specimen

Figure 5-54. Failed Boron-Epoxy Torque Arm Specimen

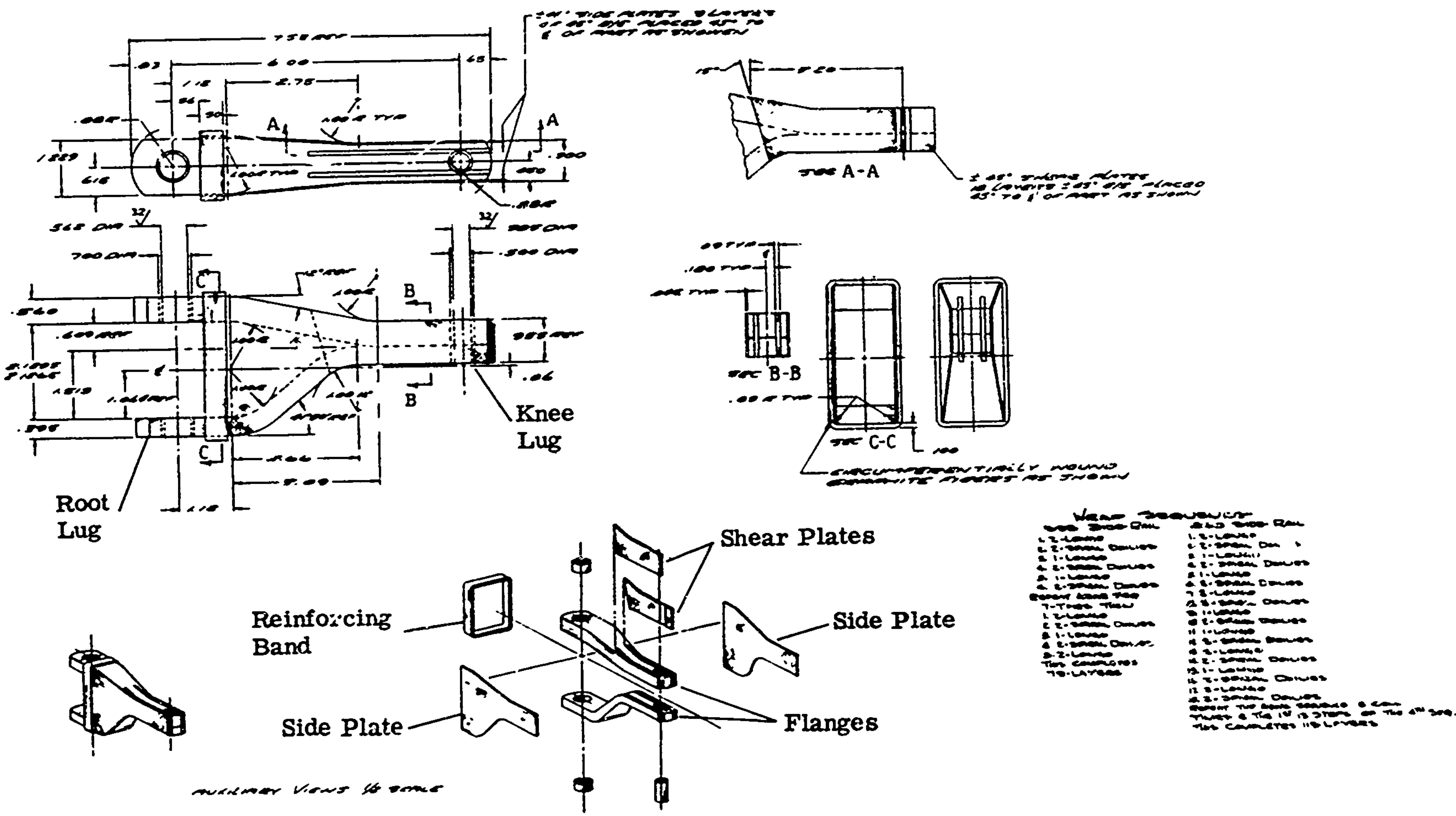



Figure 5-55. Boron-Epoxy Torque Arm (Proposed Design)

#### 5.3.1.3 Boron-Epoxy Outer Cylinder

Two design concepts were explored. The first concept involved bonded joints for the primary attachments. Tests on trial specimens simulating the socket joint between the cylinder and trunnion fitting pointed up the difficulty in supporting high intensity loads with bonded type joints. A mechanical type joint was developed during the specimen trials which performed satisfactorily. A second prototype outer cylinder design concept was developed which incorporates the mechanical type of joint.

1. Bonded Joint Concept (Prototype Assembly)

The originally considered boron-epoxy outer cylinder-trunnion design is depicted in Figure 5-56. In this case, the steel attachment fittings are fastened to the boron-epoxy cylinder by adhesive bonding.

The originally conceived design specified a variable winding pattern to accommodate different loading conditions between the top and bottom of the cylinder. A $0°_3$, ±45°, 90° laminate pattern is specified in the upper region and a 0°, ±45°, 90° pattern in the lower region. The purpose of this design is to achieve some degree of weight optimization.

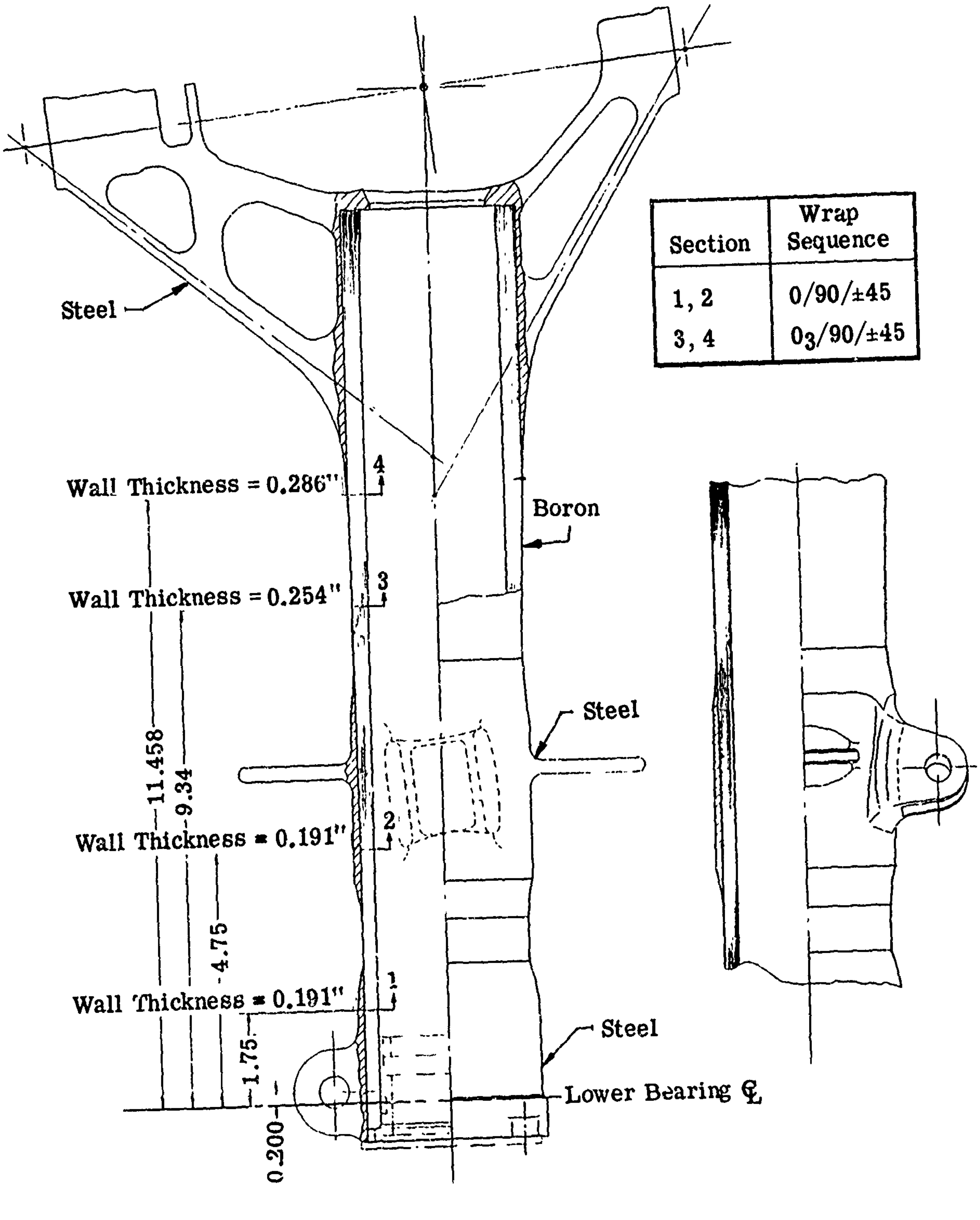
It was subsequently decided that, although this idea is a feasible one, considerable additional effort would be required to develop processing techniques to fabricate a suitable transition zone between the two regions. Since development efforts of this nature were not within the scope of this study, the design was later modified to a continuous laminate pattern.

This design indicates the joining of the trunnion and side brace fittings to the boron-epoxy cylinder by cementing the two members together with epoxy adhesive. Trial tests of the trunnion fitting joint resulted in premature failure of the bond apparently due to the stress concentration and peeling action at the lip of the socket. This pointed up the difficulty involved in designing fittings subjected to high intensity loadings in such a way as to reduce stress concentrations to a level low enough to accommodate low ductility, low strength, bonding agents It was decided to bypass altogether what might well be a futile problem by utilizing a mechanical type joint developed during the trial specimen tests.

The resulting assembly is illustrated in Figure 5-80, and is discussed later in this report.

Outer Cylinder Trial Specimen Tests

Three basic cylinder specimens were fabricated and tested in this program. The specimens are designated as the ten-ply, the forty-eight-ply, and the thirty-two-ply specimens. The originally intended designs are illustrated in Figures 5-57, 5-58 and 5-59. The ten-ply cylinder was produced primarily as a fabrication trial to check out the layup, winding, and bonding processes. The forty-eight and thirty-two-ply cylinders were intended to simulate the landing gear outer cylinder design of Figure 5-56 in both construction and loading configuration. The fabrication details associated with these specimens are given in Paragraph 8.2.5.1. The test experience and design evolution associated with each of these specimens is described below.




| Section | Wrap Sequence |
|---|---|
| 1, 2 | 0/90/±45 |
| 3, 4 | $0_3$/90/±45 |

Figure 5-56. Boron-Epoxy Outer Cylinder-Trunnion Assembly

Ten-Ply Cylinder Figure 5-57

This specimen was loaded by Bendix in a manner similar to that indicated in Figure 5-62. The predicted rupture load of the cylinder was 4850 pounds. On the first attempt, the loading lug twisted off the tube at less than 1000 pounds. Visual inspection indicated a poor bond between the lug ring and the tube.

The loading lug and tube were returned to Hercules for rebonding. At this point Hercules undertook a study to improve the bonding procedure, reference Paragraph 8.2.5.1. The lug and cylinder were rejoined and returned to Bendix for testing.

On the second attempt, the cylinder ruptured at a load of 3800 pounds in the manner shown in Figures 5-60 and 5-61. The rupture appeared to have initiated at the edge where the cylinder enters the steel socket. Rupture occurred at 84 percent of predicted load. Failure at less than calculated load may be due to local load concentrations at the joint entrance acting on the thin wall cylinder ($D/t = 60$) which were not accounted for in the stress calculations. These calculations are given in Appendix E-1, Item 1.

Forty-Eight-Ply Specimen

Original Design

Using the processing experience derived from the ten-ply trials, the specimen configuration shown in Figure 5-58 was fabricated next. This ply pattern is identical to that to be used in the outer cylinder prototype, Figures 5-56 and 5-80. This specimen was instrumented and mounted in the loading rig as shown in Figures 5-62 and 5-63. The predicted rupture load for this configuration was 18,000 pounds. The stress calculations pertaining to this prediction are shown in Appendix E-1, Item 2.

The test specification required loading in three steps:

1. Load to 4000 pounds and unload

2. Load to 8000 pounds and unload

3. Load to 18000 pounds and unload

The specimen successfully sustained the first two loading steps with no signs of damage or permanent set. During the attempt to achieve step 3 loading, a loud report was heard accompanied by a sudden drop in load. The maximum load achieved at this instant was 8760 pounds.

Examination of the specimen revealed a separation of the bond between the cylinder and the steel socket fitting on the upper or tension side of the cylinder, Figures 5-64 and 5-65. (Point A in Figure 5-58.) No other damage was apparent either to the composite cylinder, the steel fittings or the bonded joint between the loading lug and the cylinder.

Next an attempt was made to remove the cylinder from the steel socket without damaging either the cylinder or the fitting. The intention was to inspect the interface between the

cylinder and the fitting for bond quality. Also it was desired to rejoin the undamaged pieces and make another attempt at a successful structural test.

First an attempt was made to separate the tube from the fitting by twice applying a 4000 pound jack load, first in the reverse direction, and then in the original loading direction. No perceptible turning of the cylinder in the socket was achieved. The specimen was then removed from the structural test rig and inserted in a press as illustrated in Figure 5-66. A load of 34,000 pounds was required to separate the tube from the fitting. Based on the total overlap area between the cylinder and fitting, this indicates that an average shear stress in excess of 3,000 psi was developed in the bonded interface during extrusion of the cylinder from the fitting.

Inspection of the tube after removal, Figure 5-67 indicated the region of bond separation (immediately above the left hand strain gage rosette). This was the only apparent region of bond separation. Also it was apparent that complete initial and sound bonding was achieved everywhere except at the very end of the cylinder along approximately one half the periphery, Figures 5-67 and 5-68.

Second Design

At this point it was decided that it would be difficult to support the high intensity socket loading without failing any high quality epoxy bond. Therefore, the joint was redesigned to rely primarily on mechanical retention for strength, Figure 5-69. This joint is intended to simulate the trunnion fitting joint concept selected for the prototype outer cylinder, Figure 5-80. The characteristics of this joint are discussed on page 5-90 (2. Mechanical Joint Concept (Prototype Assembly)).

For the test specimen of Figure 5-69, the reverse wedge was obtained by wrapping a 0°, 90° glass-epoxy reinforcement over the existing boron-epoxy cylinder and machining to the required taper angle. The existing steel socket fitting was reheat treated to 260-280 ksi UTS and machined to include the reverse taper. The cylinder end was coated with urethane and inserted into the fitting. The plug simulates the action of the orifice support tube (Figure 6-6) in providing support against collapse of the open end of the tube when subjected to bearing pressure between the cylinder and the fitting. The plug is held in place by the setscrew. The retainer plate simulates the supporting action of the lock nut.

The same loading sequence as for the original design was applied in test. This configuration sustained a load P of 9600 pounds. Failure was by compressive crushing of the composite cylinder at the lower edge of the socket, Point B Figure 5-69. Photographs of the failure are shown in Figures 5-70 and 5-71.

It is notable in this case that the load was supported without joint separation. Failure was due to rupture of one of the members, and not be separation of one member from the other.

### Third Design

It was apparent that further information regarding the strength of this type of socket joint could be obtained by cropping off the end of the failed tube and building up a second joint using the original steel fittings. For this purpose the design of Figures 5-73 and 5-74 were evolved.

Two significant load levels were achieved with this version.

> 1 - With the loading lug in the position indicated by the solid outline, Figure 5-73, a load P of 14,000 pounds were achieved. At this load an adhesive failure was sustained between the loading lug and the composite cylinder by shearing action along the circumferential surface marked "C." The average shear stress generated along this surface was calculated to be 3360 psi.
>
> 2 - After failure of the joint, the loading lug was rotated to the position shown by the broken outline. It was rotated to this position by increasing the jack load where it was held to a 0.75 inch offset by friction between the lug fitting and the composite cylinder. The jack load reached a level of 22,000 pounds when the cylinder ruptured within the socket at location "D." The failure was a complete circumferential separation leaving one section of the cylinder intact within the socket, Figures 5-75 and 5-76.

It is not clear whether the rupture initiated at the top on the "tension" side or at the bottom on the "compression" side. Again, this design succeeded in sustaining the load without separation of the joint.

### Summary, Forty-Eight-Ply Specimen

The test experience with the forty-eight-ply cylinder specimen is summarized in the following tabulation.

| Design | Failure Location | Shear (P) Lbs. | Bending Moment In. Lbs. | Torque In. Lbs. |
|---|---|---|---|---|
| Original | | 18,000 | 212,000 | 64,500 |
| Original | Socket | 8,760 | 103,000 | 31,400 |
| Second | Socket | 9,600 | 118,000 | 34,000 |
| Third | Load Lug | 14,000 | 76,200 | 50,200 |
| Third | Socket | 22,000 | 120,000 | 16,000 |

The loads shown are the nominal loads on a cross section of the cylinder at the lip of the socket. Because of the differing geometry among specimen tests the loads are given at this location to provide a common measure of the loading on the joint which is the critical structural detail in the outer cylinder design.

The first entry corresponds to the theoretical strength of the cylinder taken simply as a beam, i.e., ignoring local effects due to contact with the socket. In other words this is the basic strength of the cylinder for this particular loading combination. Comparing this with the loads where failure occurred in the socket it is apparent that the joint strength is considerably less than the basic cylinder strength. In order to develop the full capacity of the cylinder, the strength of the joint must be increased. This can be done in a couple of ways.

1. In all cases failure was due to rupture of the tube wall within the socket. This points to an increase in cylinder wall thickness which need be confined to the region of the socket only. A theoretical procedure was developed for predicting tube wall rupture within the socket which correlates well with test results on this specimen and for others. Using this procedure the locally reinforced trunnion socket design shown in Figure 5-80 was arrived at for the landing gear outer cylinder.

2. A C-scan inspection of the composite cylinder revealed a one-inch wide band of delamination along the entire length of the cylinder. This flaw is apparent in the cross sections shown in Figures 5-71 and 5-72. The delamination is noticeable where white chalk was rubbed into the ply separations which coincide in orientation with the location indicated by the C-scan. See Figure 8-59 for the C-scan results.

This flaw somewhat clouds the issue on the actual design integrity of this particular socket joint. Nevertheless, a local cylinder wall reinforcement within the socket is an obvious requirement.

An additional conclusion to be drawn from the testing on the forty-eight ply-cylinder has to do with the bond strength of this particular laminate joined to steel. The first indication arises with the original design where in excess of 3000 psi shear stress was required to force the cylinder from the socket. A second indication was a calculated shear stress of 3360 psi required to shear off the lug fitting on the third design. These are nominal values which include the effects of stress concentrations along the joint edges.

These magnitudes are consistent with values usually quoted for this type of adhesive joint.

Thirty-Two Ply-Specimen

Original Design

The specimen as originally designed is depicted in Figure 5-77. This specimen was meant to simulate the loading and ply pattern associated with the lower end of the outer cylinder design shown in Figure 5-56. For the reasons discussed at the beginning of this paragraph, this ply pattern was discarded for use in the outer cylinder. However, this cylinder specimen had already been fabricated when this decision was made. It was decided to test the specimen anyway since useful design information applicable to the finally adopted outer cylinder design could still be obtained. However, based on the experience derived from testing the forty-eight-ply specimen, it was decided to discard the bonded type socket joint shown in Figure 5-77.

## Second Design

The design selected for the thirty-two-ply cylinder is shown in Figure 5-78 which incorporates the socket type joint finally adopted for the prototype outer cylinder-trunnion joint, Figure 5-80. The stress analysis indicated the cylinder to have a strength P = 15000 pounds with failure to occur at Point A and the loading lug to have a strength P = 13000 pounds with failure to be in shear along the joint periphery at Point B . The stress calculations are given in Appendix E-1, Item 3.

During the test the specimen failed by rupture of the cylinder in the region around Point A , Figures 5-78 and 5-79, at 13000 pounds. Therefore the cylinder sustained a load of 13/15 or 0.87 of the predicted value. This test also indicated that the loading lug joint was capable of supporting a shear stress in excess of 3360 psi.

A C-scan inspection of the composite cylinder indicated some possible regions of delamination within the cylinder wall as fabricated. These lapses in structural integrity might have had some influence on the specimen falling somewhat short of the target load. The details of the C-scan inspection are given in Figure 8-60.

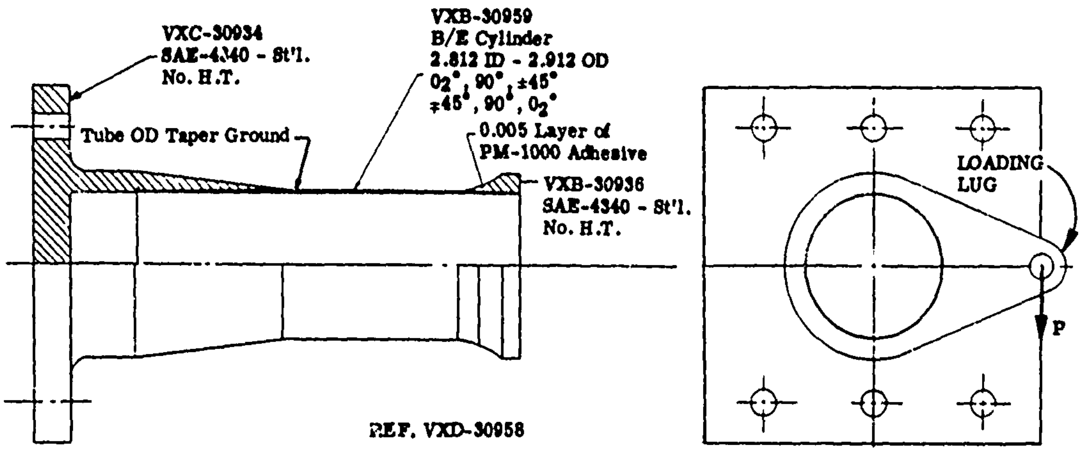



Figure 5-57. Outer Cylinder Specimen, Boron-Epoxy, Ten-Ply

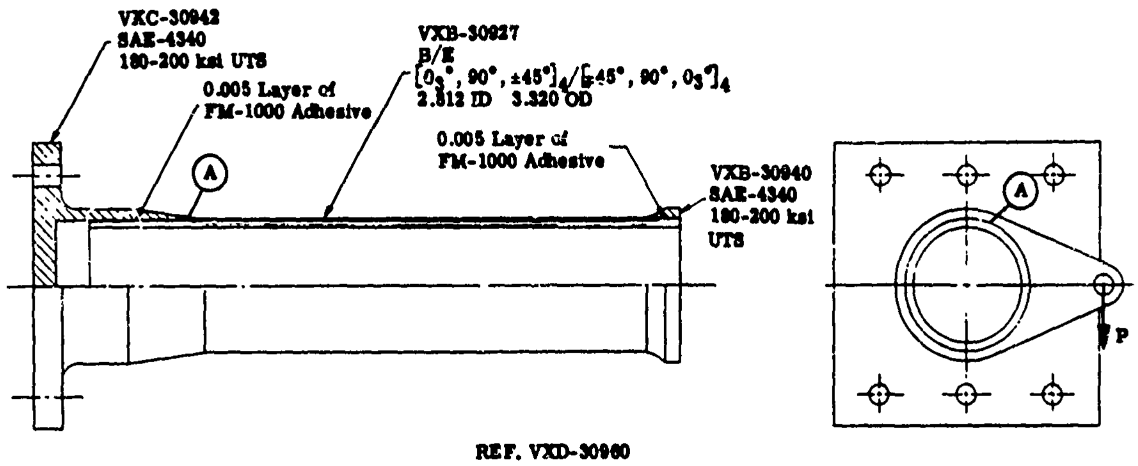



Figure 5-58. Outer Cylinder Specimen, Boron-Epoxy, Forty-Eight-Ply (Original Design)

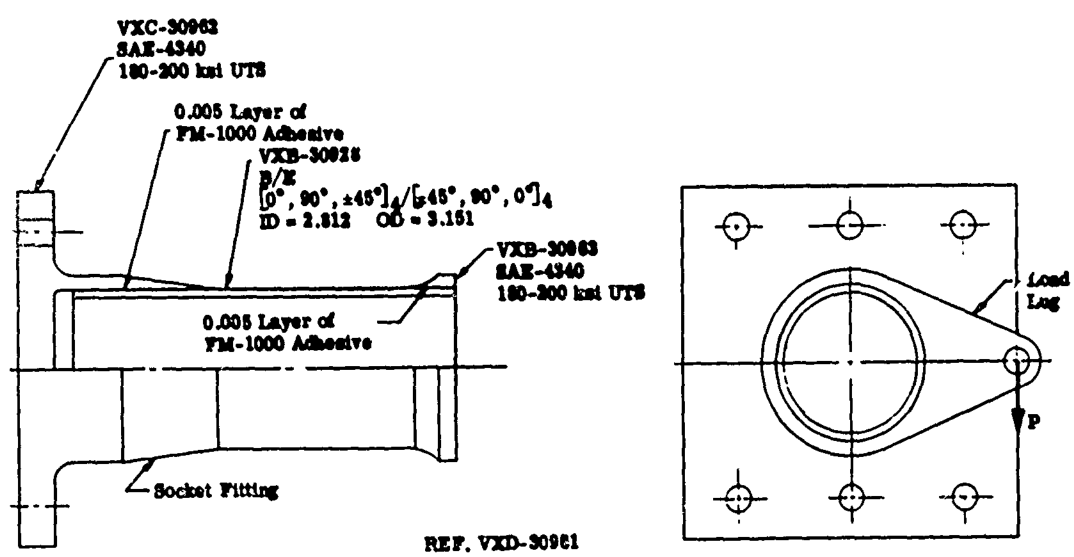



Figure 5-59. Outer Cylinder Specimen, Boron-Epoxy, Thirty-Two-Ply

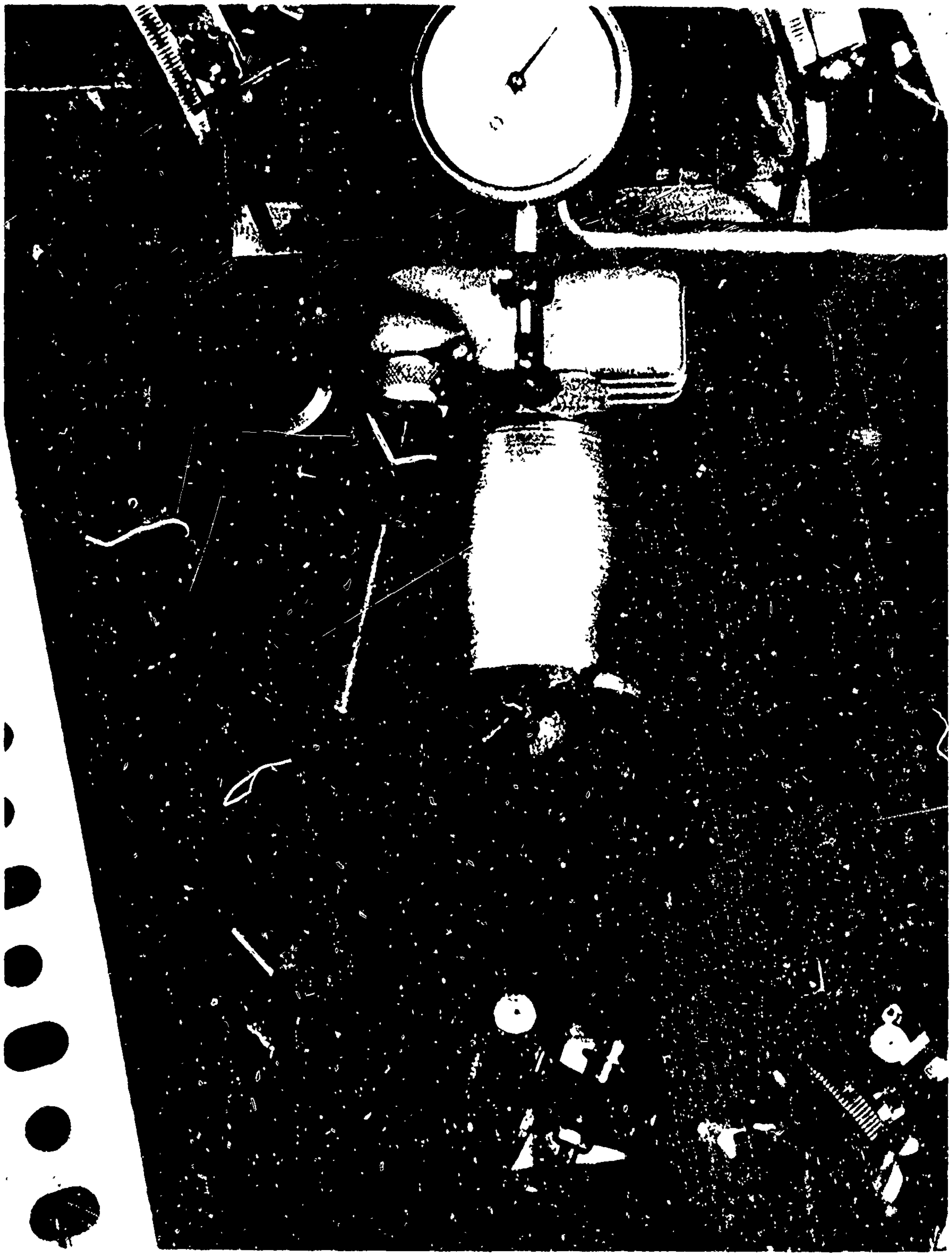


Figure 5-60. Ten-Ply Cylinder Specimen - Top View

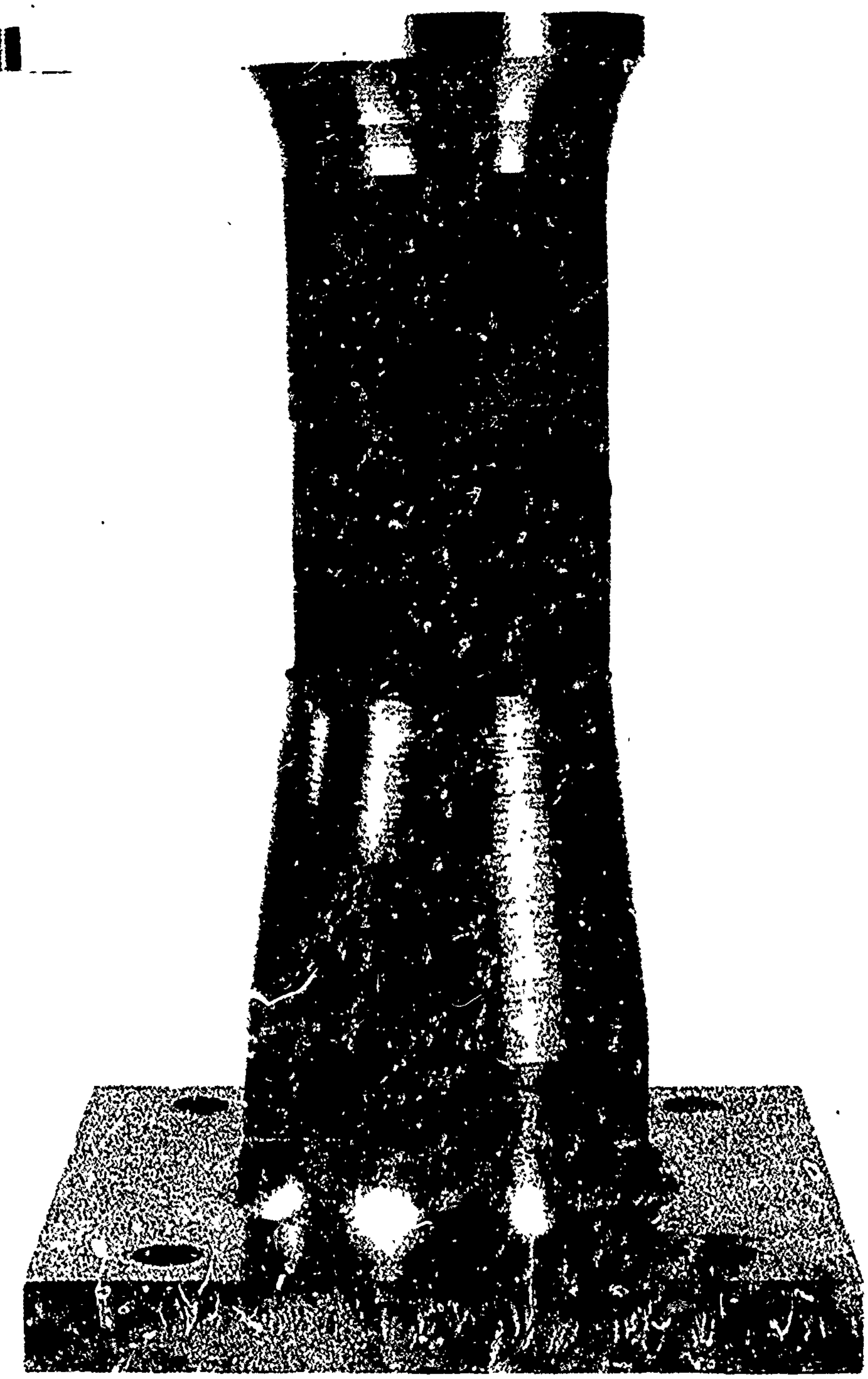


Figure 5-61. Ten-Ply Cylinder Specimen

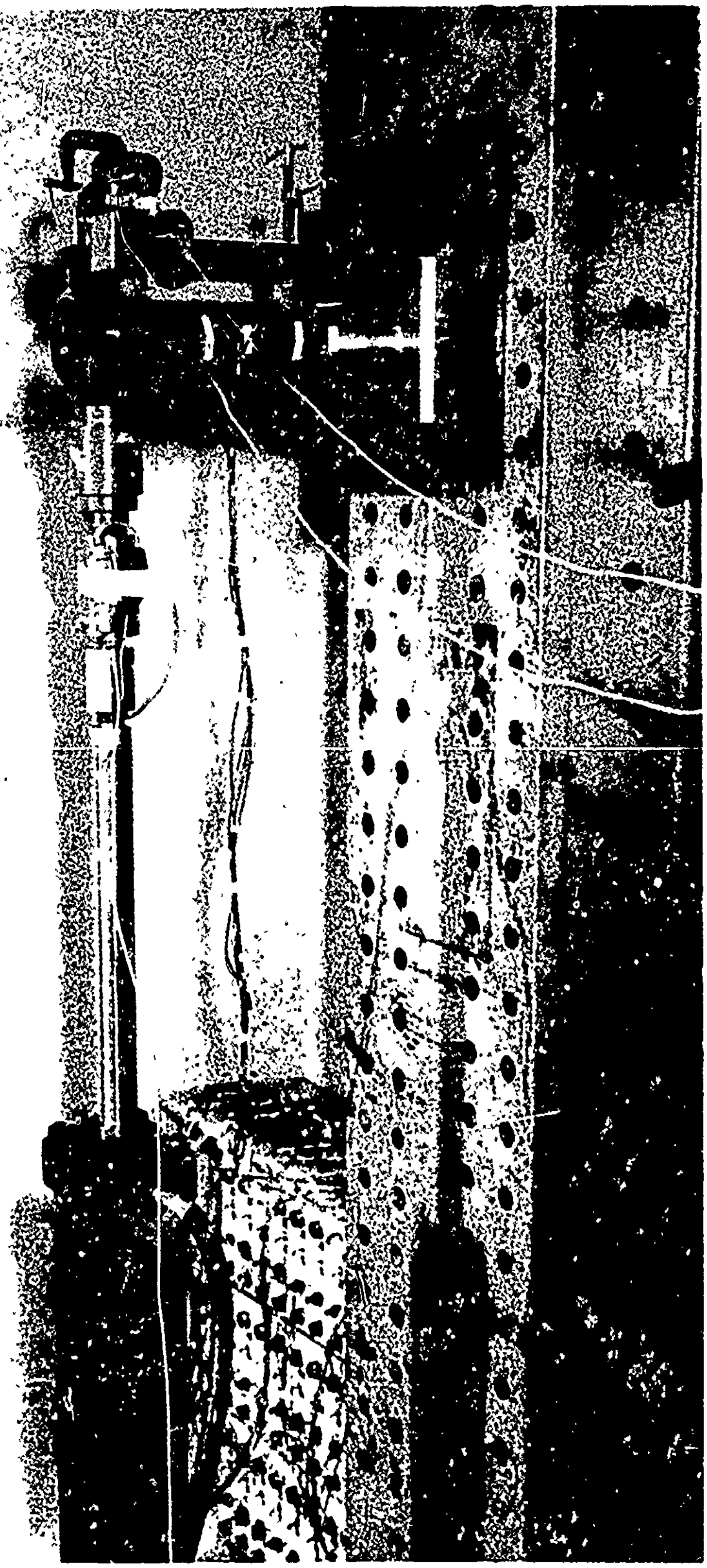


Figure 5-62. Test Setup - Forty-Eight-Ply Cylinder Specimen (Original Design)

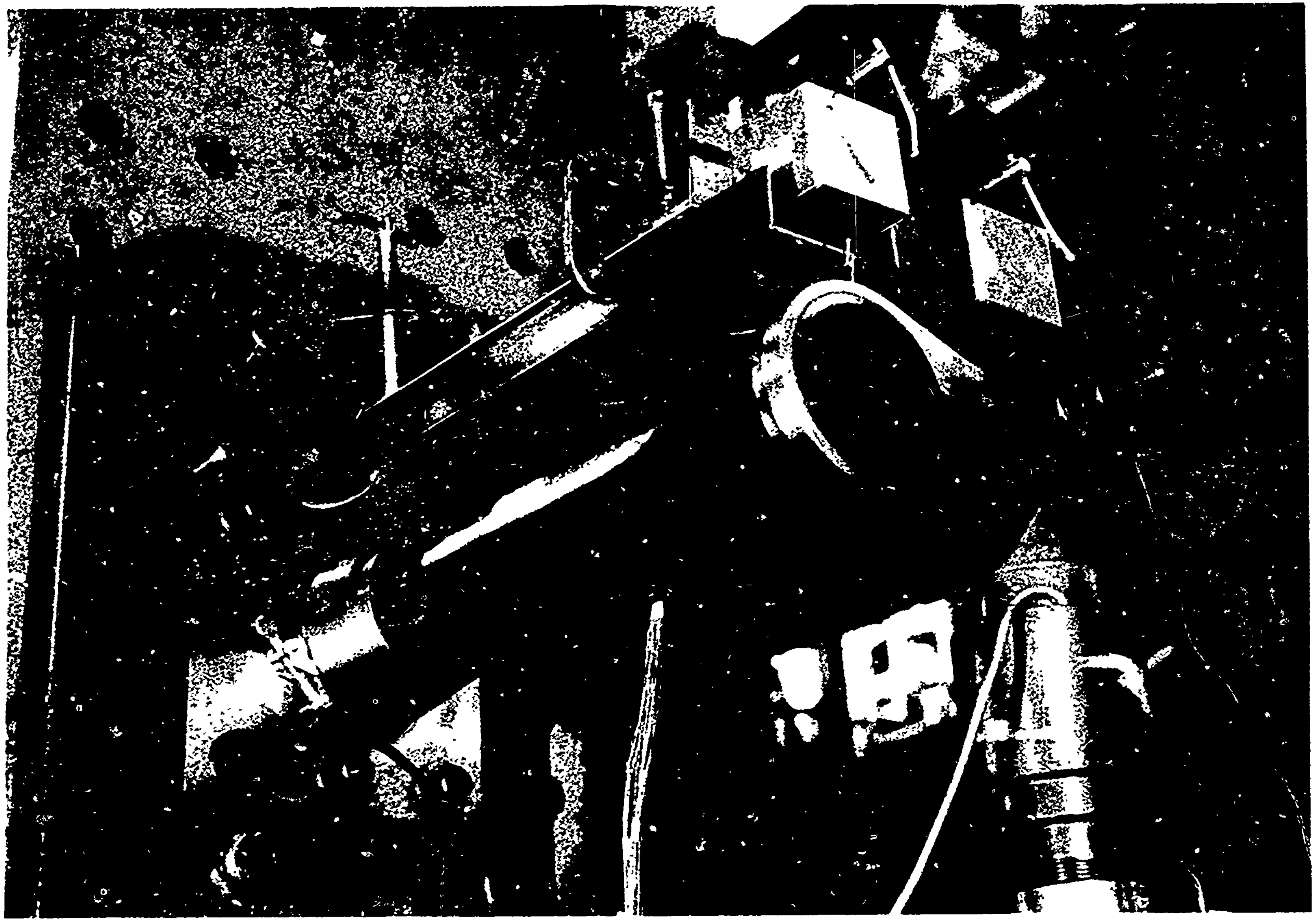


Figure 5-63. Test Setup - Forth-Eight-Ply Cylinder Specimen (Original Design)

Figure 5-64. Bond Separation - Forty-Eight-Ply Cylinder Specimen (Original Design)

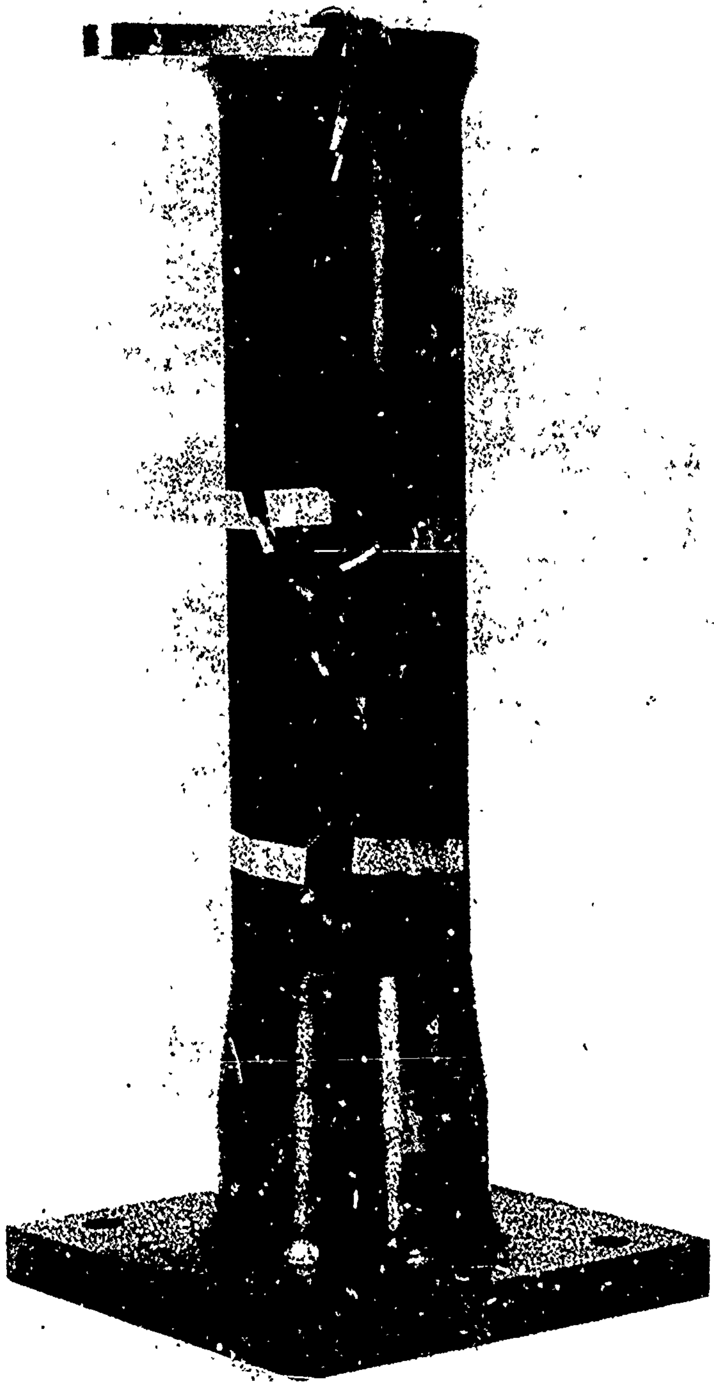


Figure 5-65. Forty-Eight-Ply Specimen After Test (Original Design)

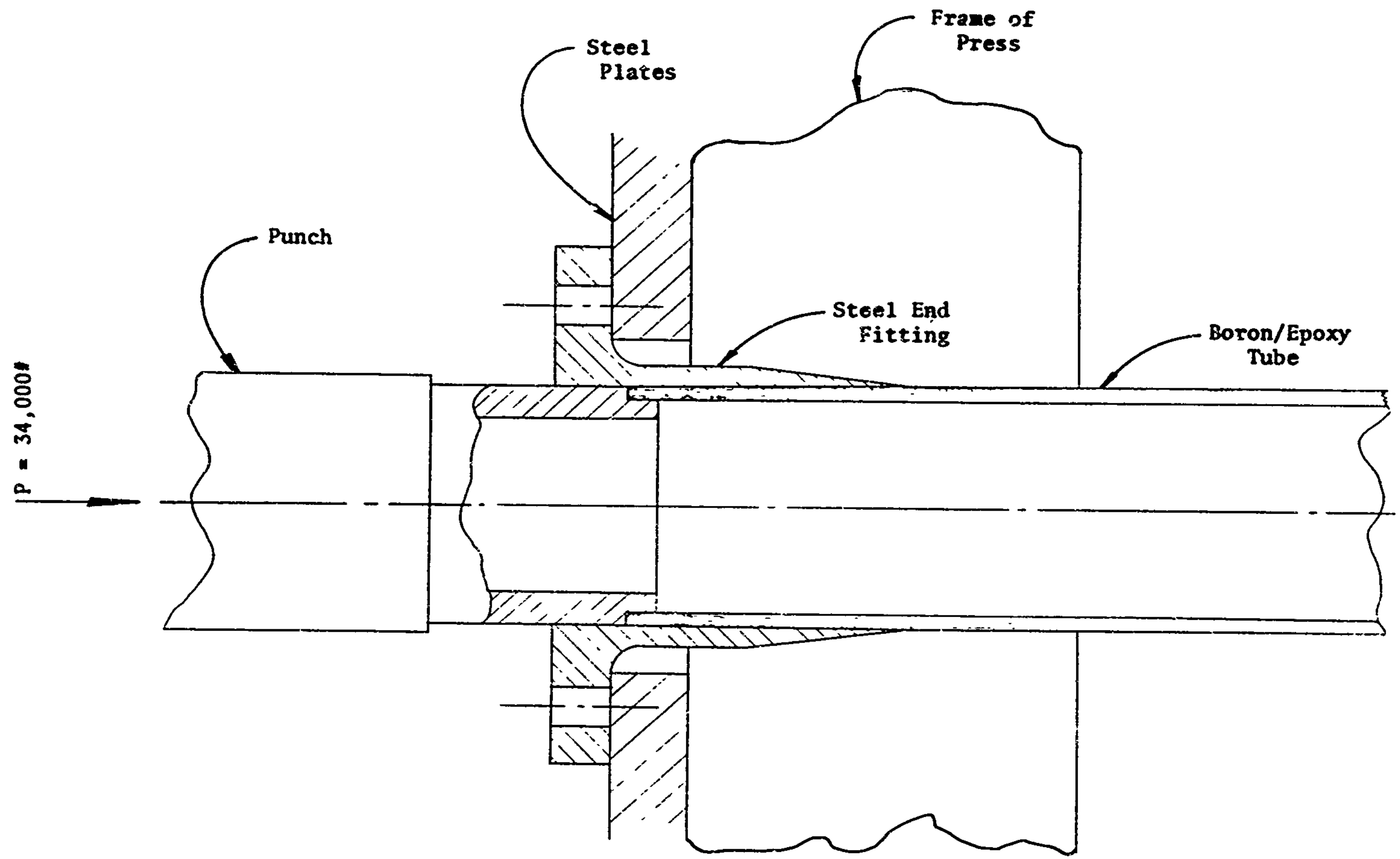



Figure 5-66. Removal of Cylinder from Fitting

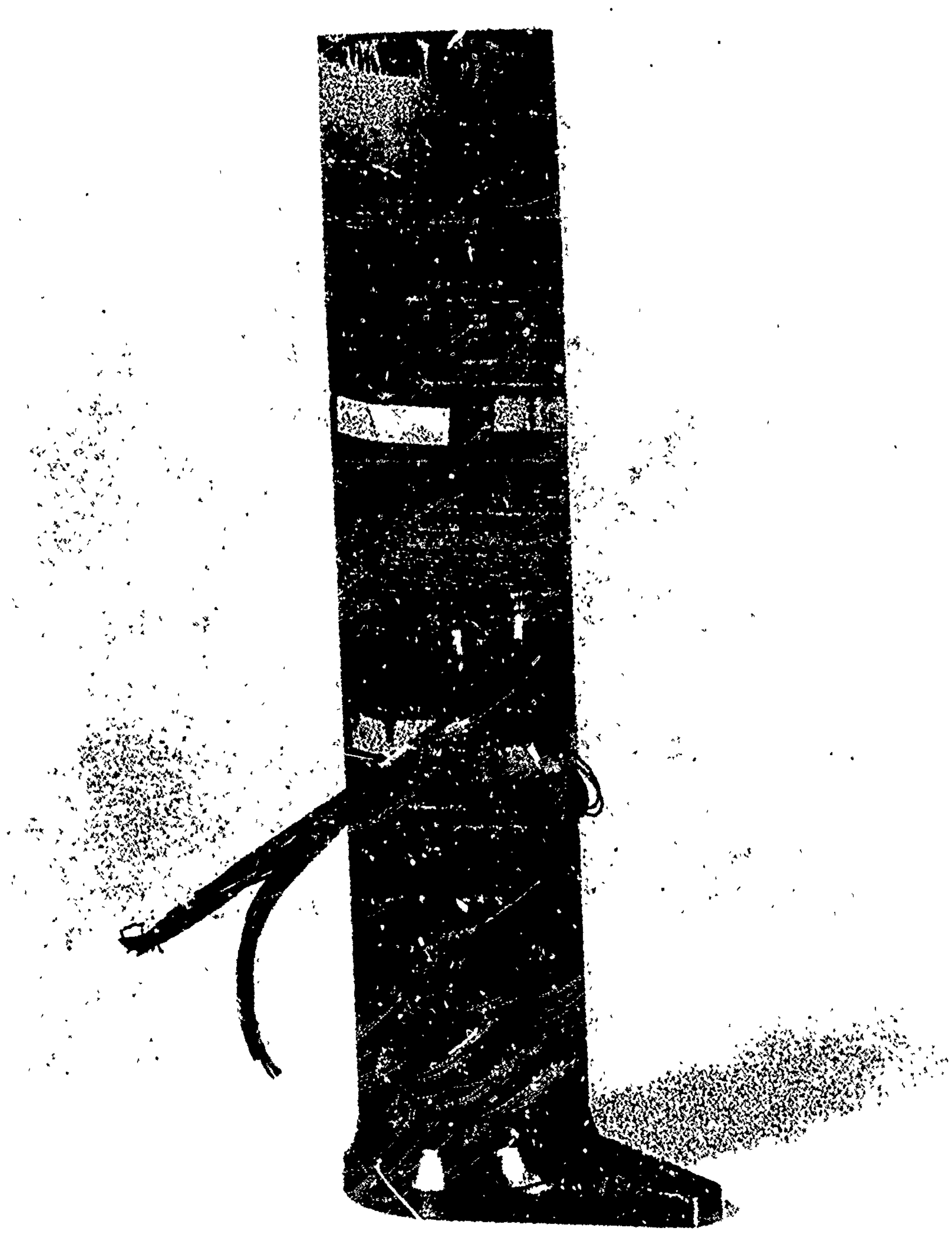


Figure 5-67. Cylinder Removed from Fitting

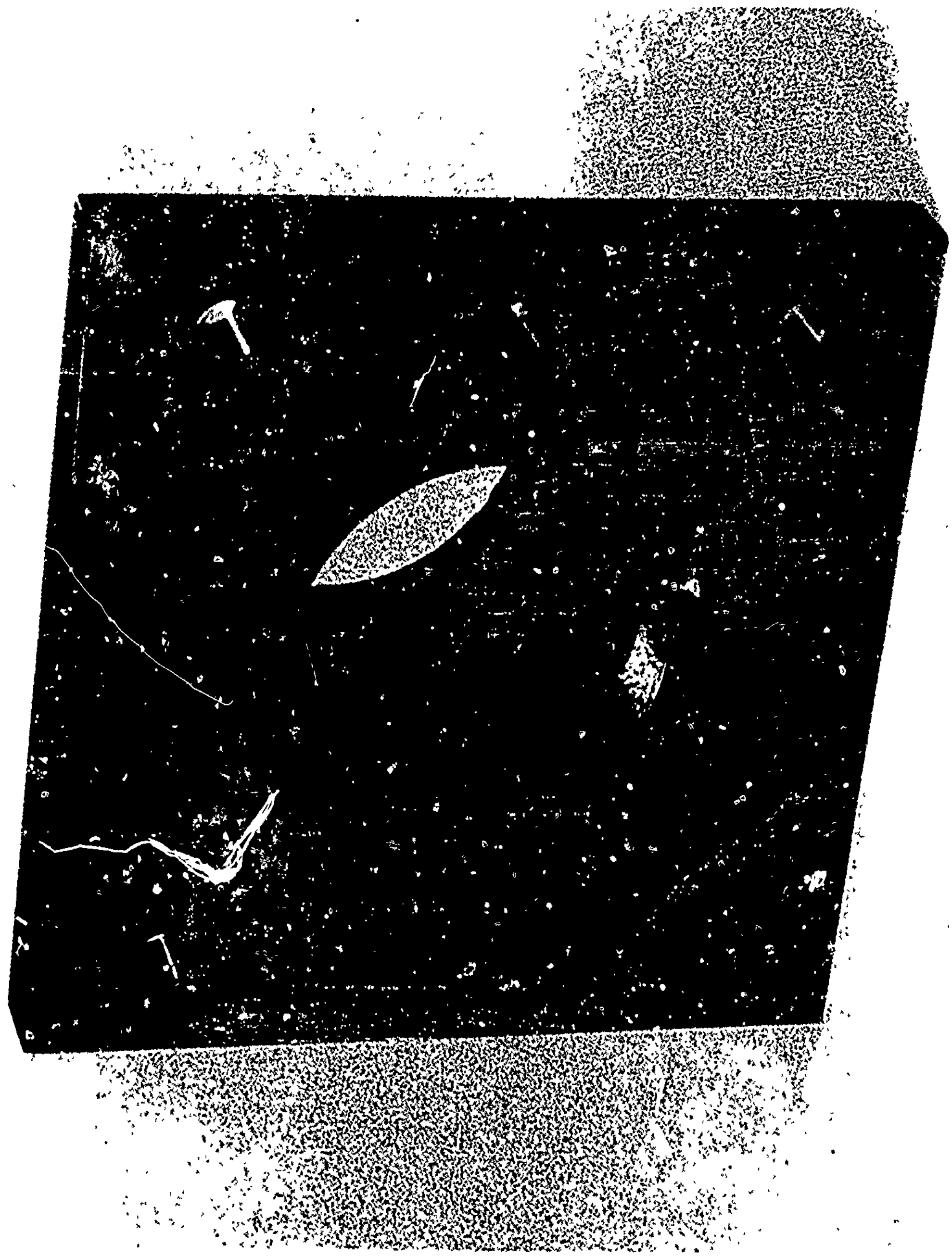


Figure 5-68. Socket Fitting after Removal of Cylinder

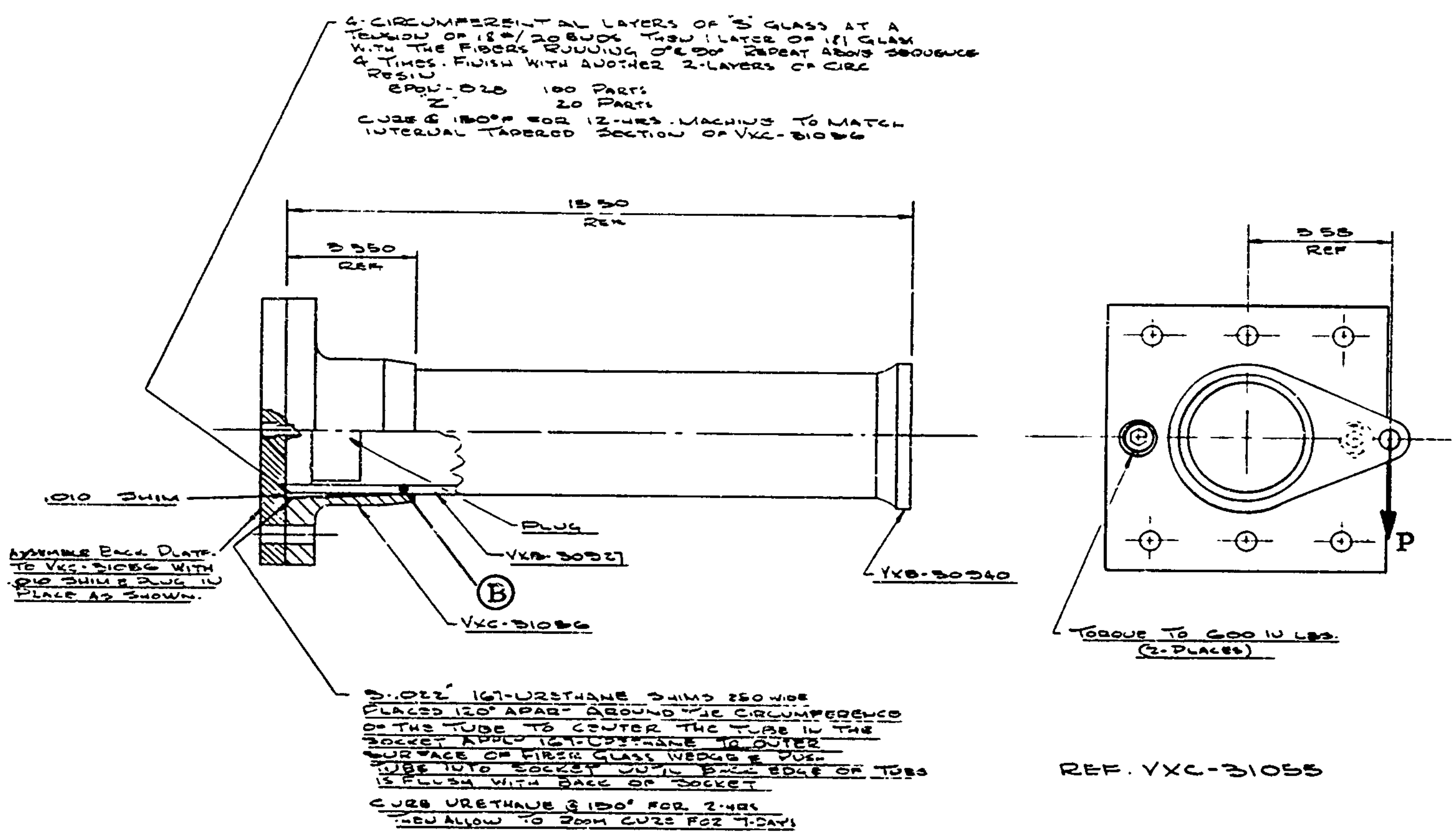



Figure 5-69. Boron-Epoxy Cylinder Specimen, Forty-Eight-Ply (Second Design)

Figure 5-70. Failed Forty-Eight-Ply Cylinder Specimen, Front View (Second Design)

Figure 5-71. Failed Forty-Eight-Ply Cylinder Specimen, Back View (Second Design)

Figure 5-72. Failed Forty-Eight-Ply Cylinder (Second Design)

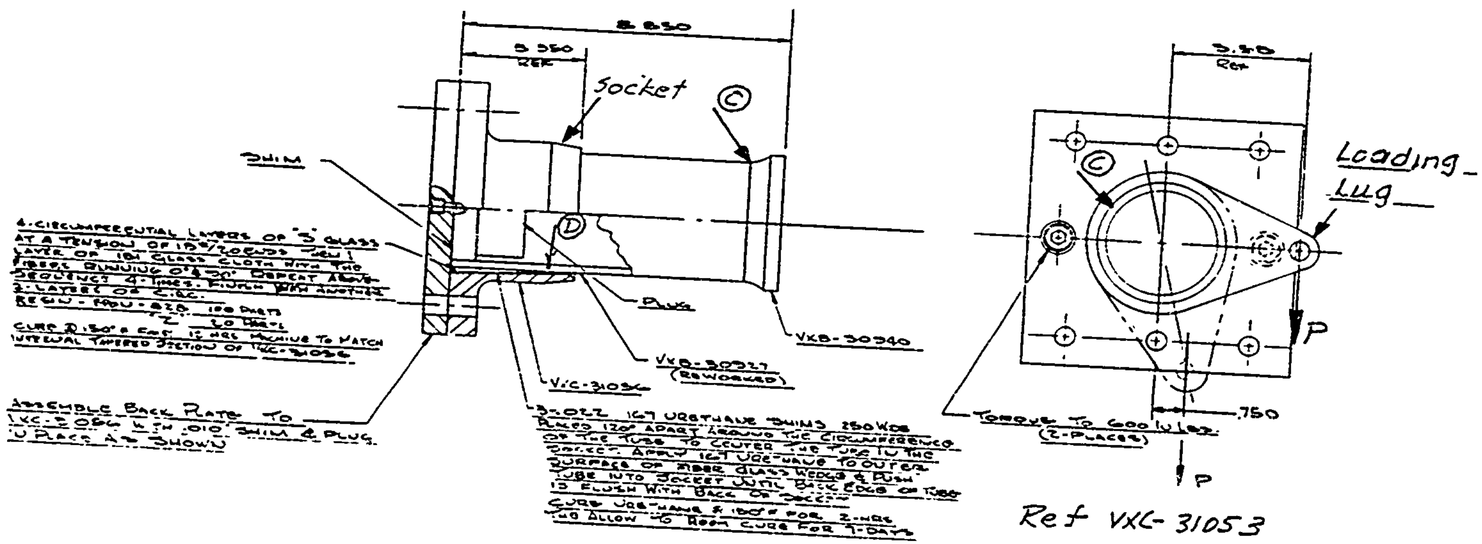



Figure 5-73. Boron-Epoxy Cylinder Specimen, Forty-Eight-Ply (Third Design)

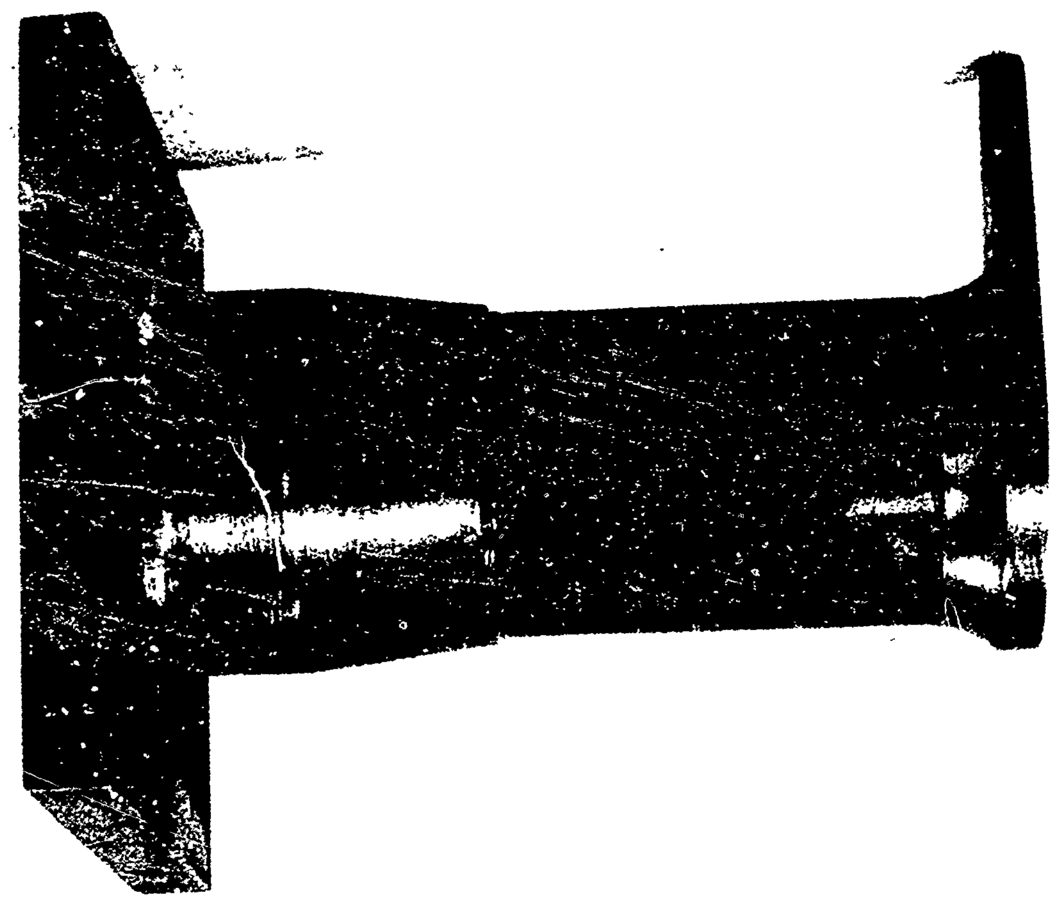


Figure 5-74. Boron-Epoxy Cylinder Specimen Before Test

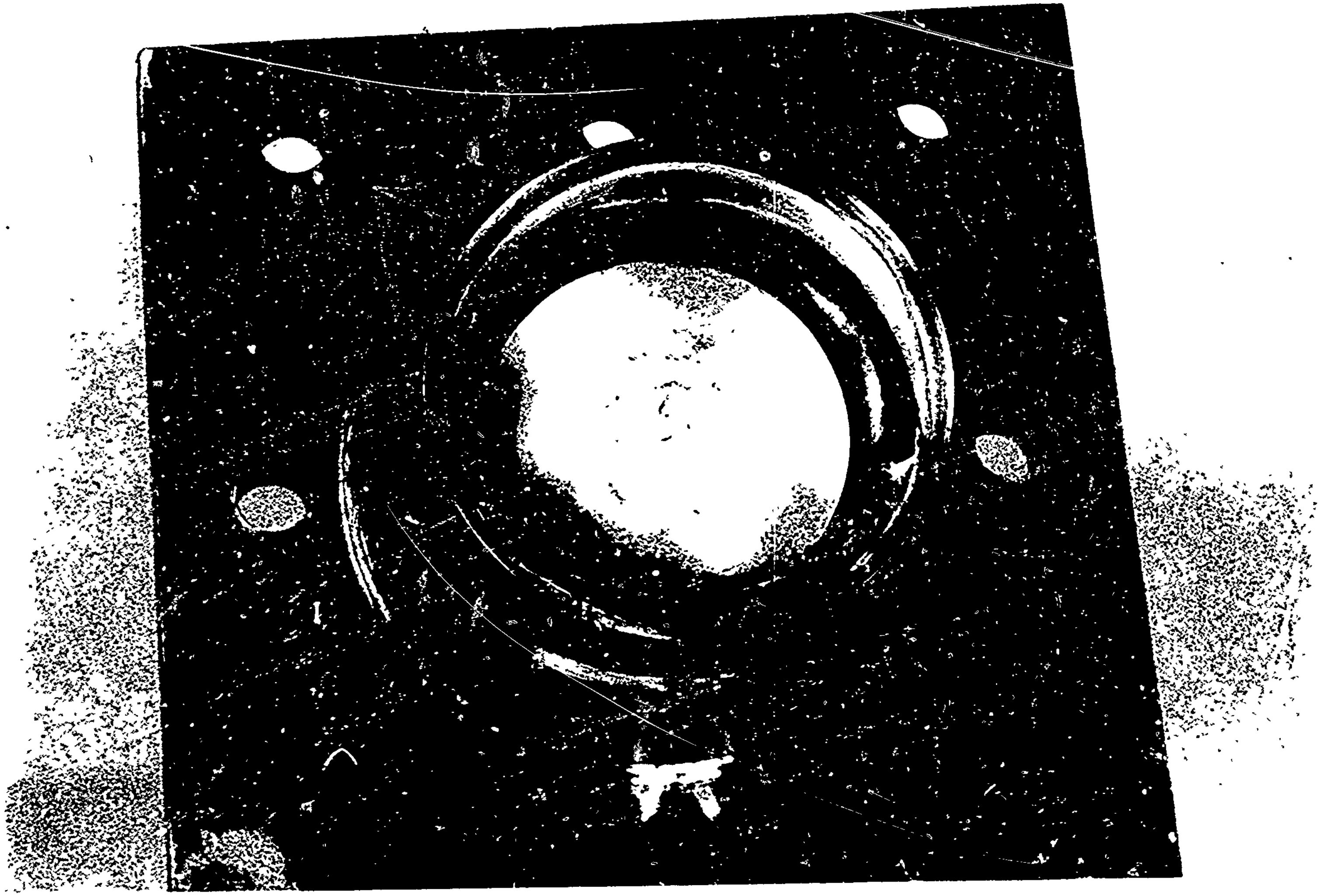


Figure 5-75. Failed Forty-Eight-Ply Cylinder, Boron-Epoxy, (Third Design)

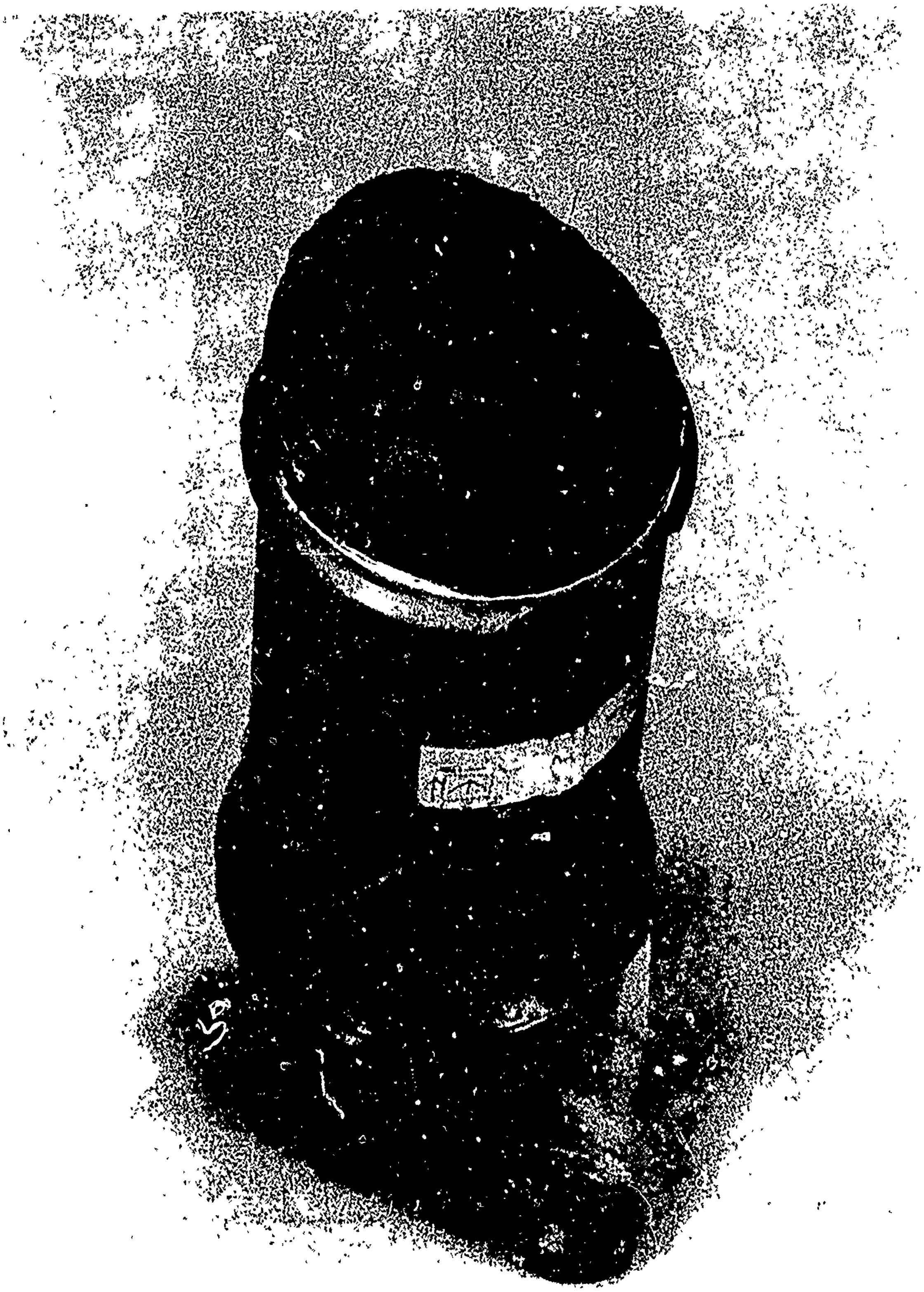


Figure 5-76. Failed Boron-Epoxy Forty-Eight-Ply Cylinder (Third Design)

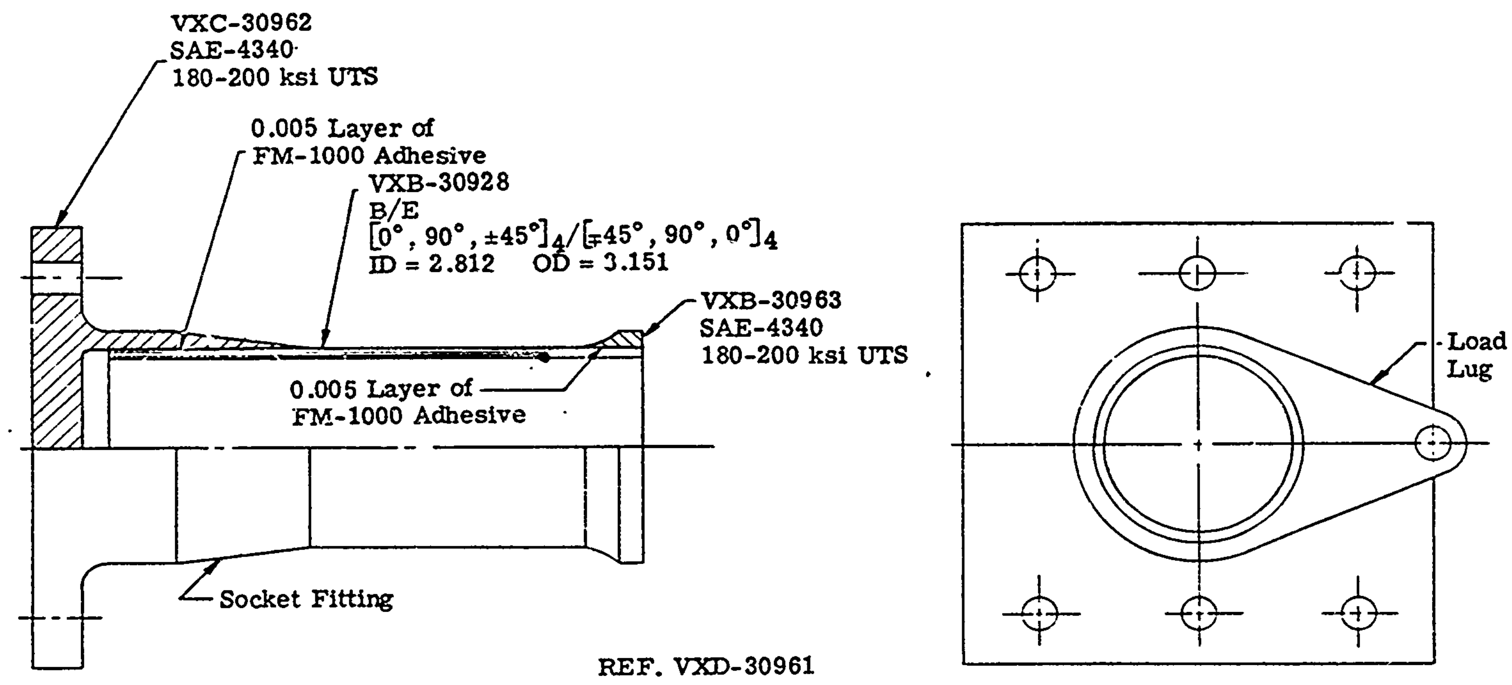



Figure 5-77. Cylinder Specimen, Boron-Epcxy, Thirty-Two-Ply (First Design)

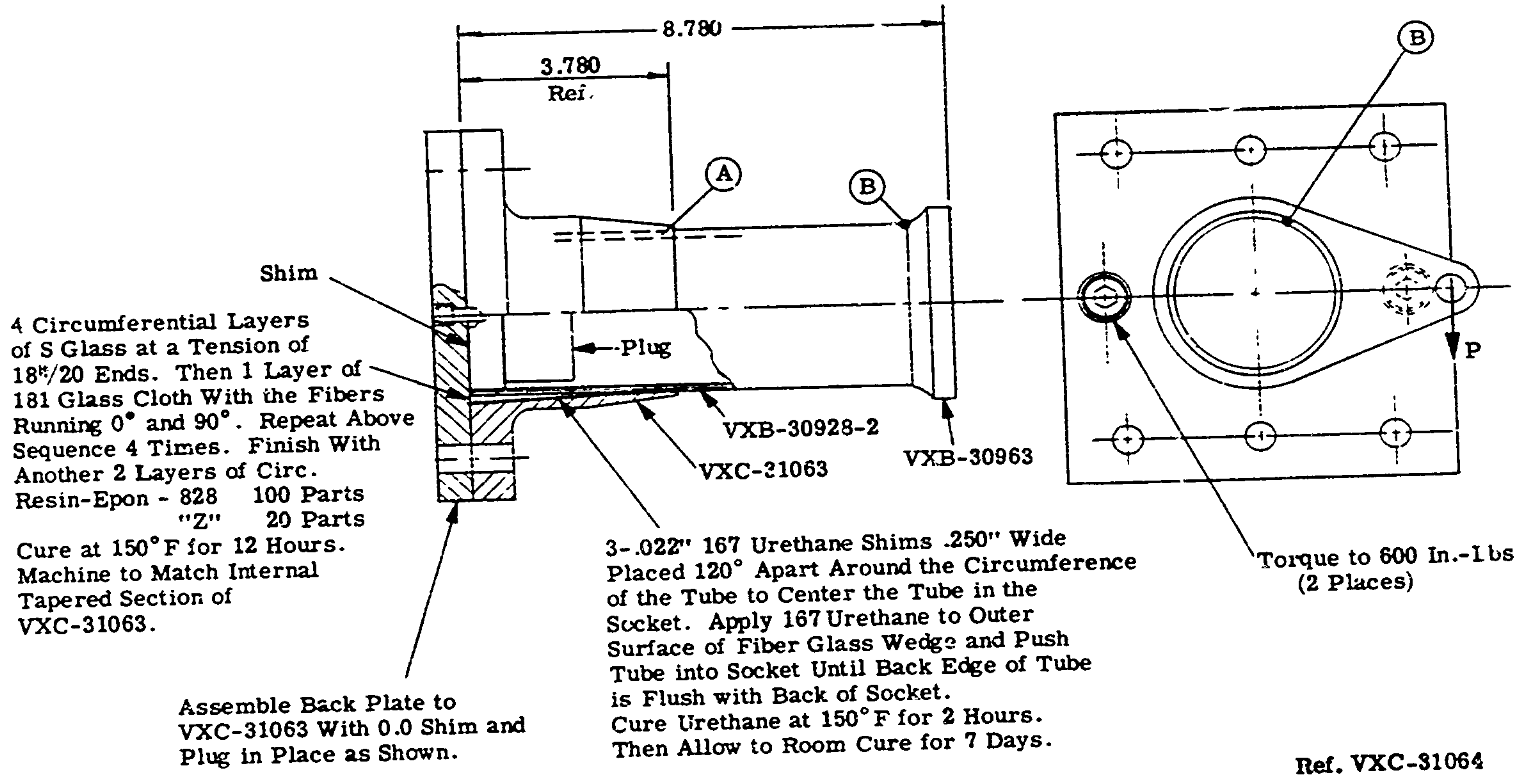



Figure 5-78. Cylinder Specimen, Boron-Epoxy Thirty-Two-Ply (Second Design)

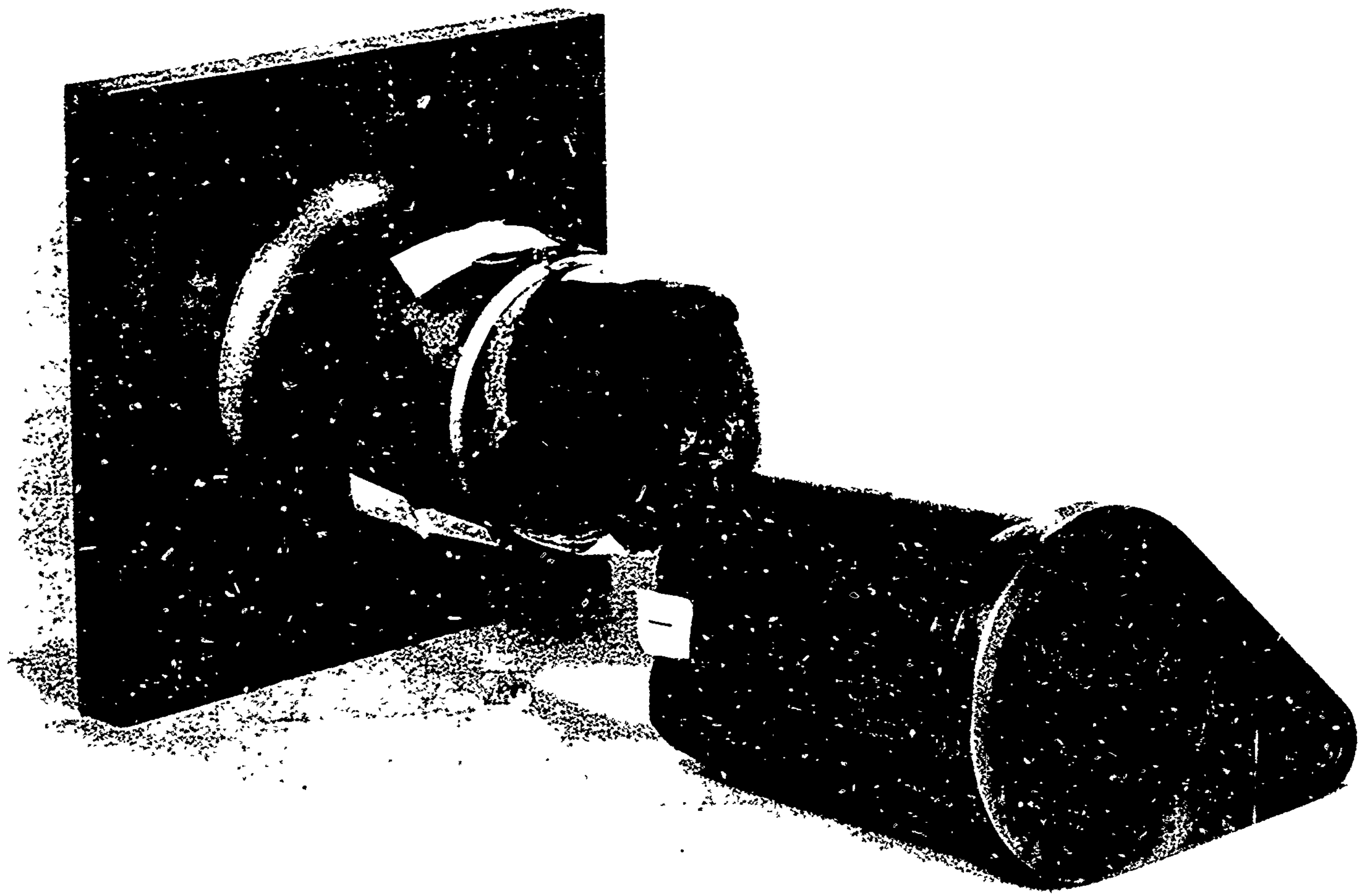


Figure 5-79. Failed Cylinder Specimen, Boron-Epoxy Thirty-Two-Ply (Second Design)

2. Mechanical Joint Concept (Prototype Assembly)

As a result of the experience derived from the Phase I design studies and trial specimen tests, the outer cylinder-trunnion design finally submitted for fabrication in Phase II is shown in Figure 5-80.

The basic structure consists of a boron-epoxy cylinder with three high-strength steel fittings attached to the outer surface.

Composite Cylinder -

A $0^\circ_3$, ±45°, 90° laminate pattern is used to form the basic boron-epoxy cylinder. The outside surface of the cylinder is ground to size after the curing cycle. A local 0°, 90° glass-epoxy buildup is applied at the side brace and trunnion fitting locations to provide gripping reinforcements for the fittings. A nickel liner is applied to the inside surface to provide leakage resistance and a hard wearing surface for the piston bearing. Refer to Paragraph 5.3.1.5 for a discussion of the liner characteristics.

Trunnion Fitting Attachment -

The trunnion end of the composite tube forms a section of a cone, with a four-degree included angle, with the large end of the cone located at the trunnion end of the tube. The conical section is formed by grinding off part of the added 0°, 90° laminates provided for the trunnion attachment. The metal trunnion fitting has a matching conical section which mates with the composite tube. A urethane layer approximately 0.020 inch thick is inserted between the fitting and the cylinder.

Joint strength is provided primarily by the mechanical entrapment of the cylinder within the trunnion fitting. Bending and tension loads in the cylinder are resisted by the wedging action of the reverse taper. Compression loads are resisted by the lock nut. Torsion loads are reacted by the circumferential friction resistance provided by the internal bearing reactions which result from the concurrent bending loads. The purpose of the urethane cushion within the joint is to prevent fretting between the mating parts, to provide friction to resist pullout and torsion loads, and to alleviate local concentrations of bearing and friction stresses.

The feasibility of this concept was proven during trial specimen tests the results of which are detailed above.

Side Brace Fitting Attachment -

This design, as with the trunnion fitting, employs a mechanical entrapment feature as the primary means of developing structural strength. The composite tube is prepared to receive the fitting assembly by grinding an enlargement on the outside diameter consisting of two conical sections located base to base. This reinforcement forms two ramps of small angle sloping away from each other toward either end of the tube. The metal fitting is designed to grip this conical reinforcement.

The fitting assembly consists of four items - the lug ring, the lower ring, the split collet, and a spanner nut, Figure 5-81. The lug ring is installed first by passing it over the

conical reinforcement from the lower end. Next the split collet is installed from the lower end by spreading it to pass over the tapered ramp. The collet is then inserted inside the lug ring and this assembly moved toward the lower end until it seats against the upper conical surface. The lower ring and spanner nut are assembled finally and the nut turned up until all parts are wedged tight against the tapered ramps on the composite tube. A coating of urethane is painted on the contact surfaces to minimize fretting.

Torque Arm Fitting Attachment-

The torque arm fitting is attached to the composite tube by an adhesive. The end of the tube is ground to provide a diametral taper of 0.20 inch per foot. The metal fitting has a matching taper. The taper is required to facilitate the application of the adhesive.

For this application an adhesive rather than a mechanical joint is used since the loading intensity is low enough to accommodate the adhesive strength. The strength of this bonded attachment was proved adequate during the trial specimen tests described above.

Fittings -

The various detailed parts designed for this assembly are shown in detail in Figures 5-82 through 5-89.

Stress Analysis -

Strength calculations associated with this component are given in Appendix E-2.

Fabrication -

The fabrication details for the outer cylinder assembly are described in Paragraph 8.2.5.2.

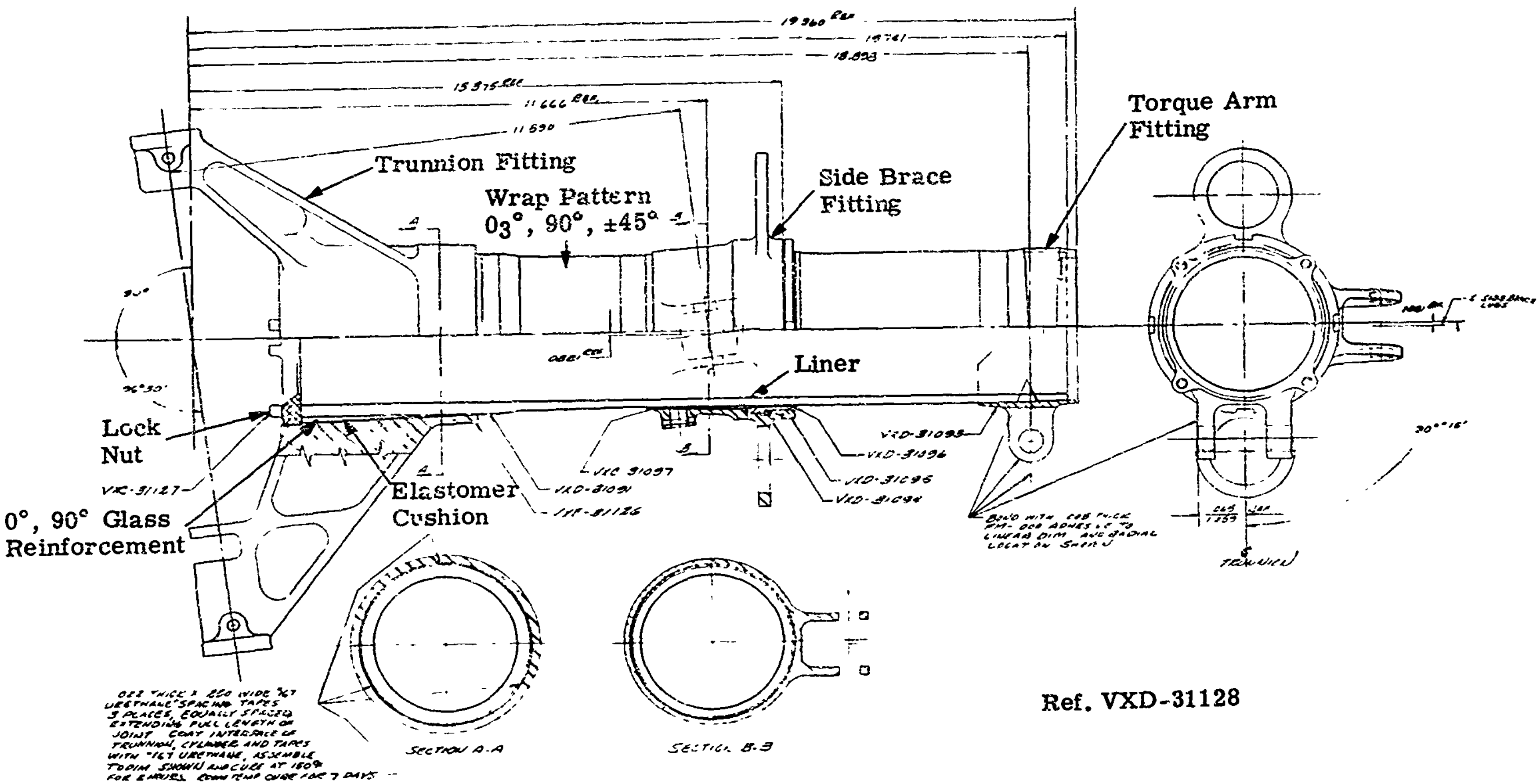



Figure 5-80. Outer Cylinder Assembly, Boron-Epoxy (Proposed Design)

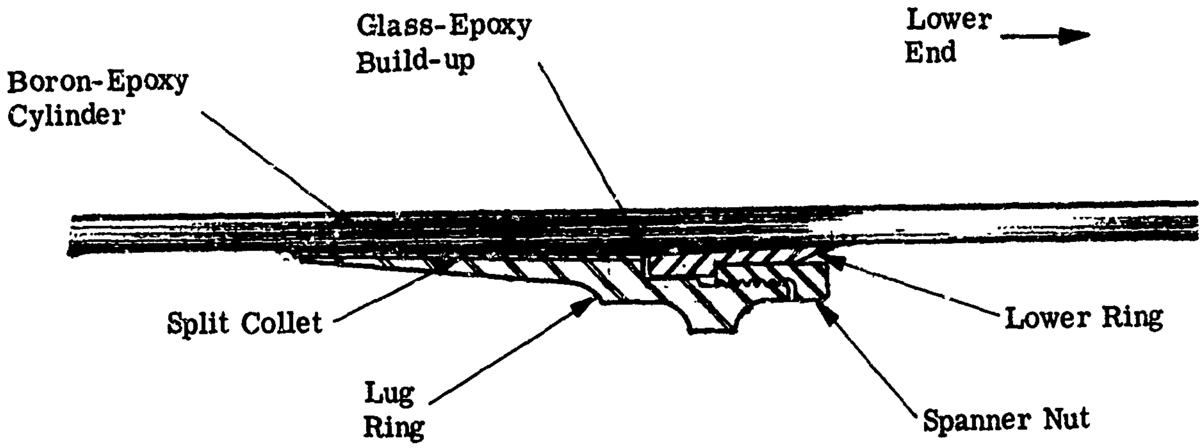
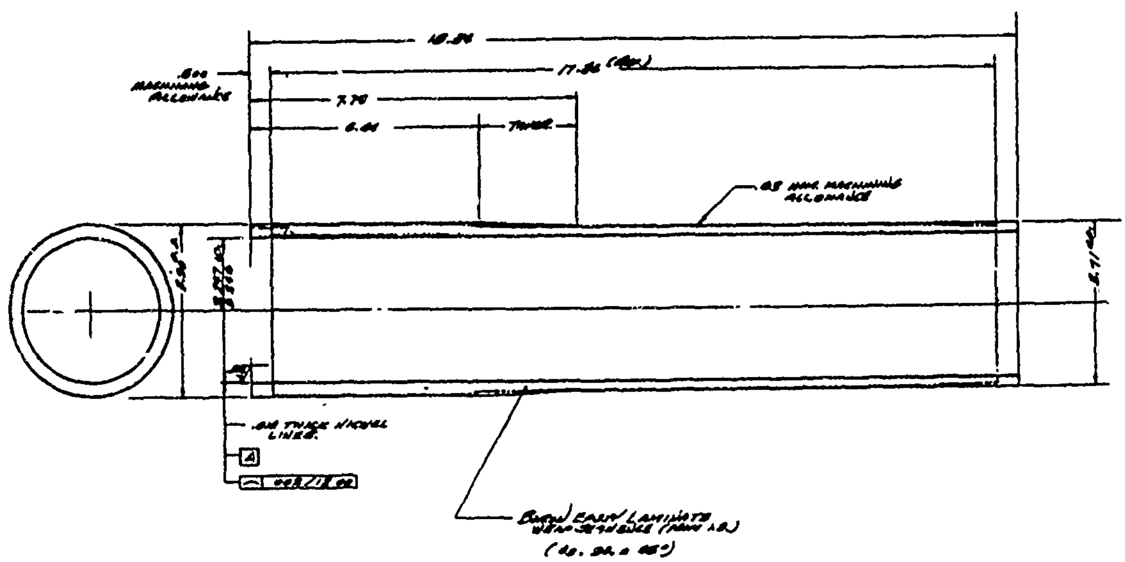
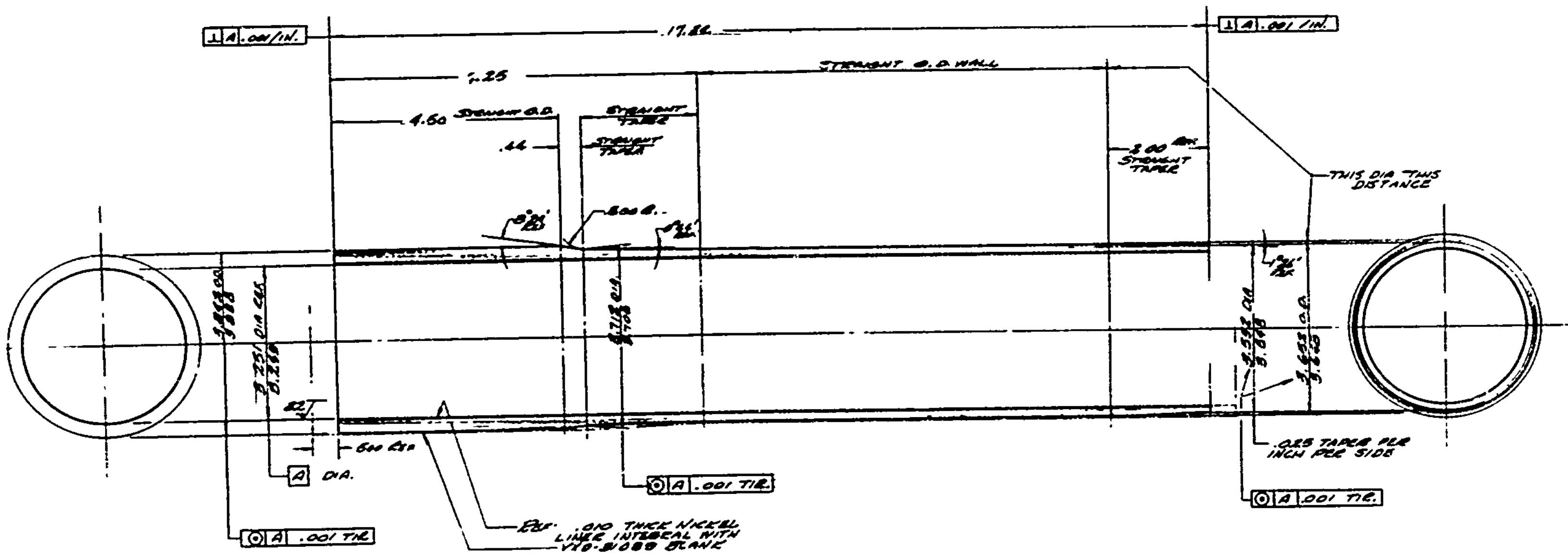



Figure 5-81. Side Brace Fitting Assembly



VXD-31089

Figure 5-82. Boron-Epoxy Filament Composite Tube for Outer Cylinder Assembly




DWG VXD-31090

Figure 5-83. Boron-Epoxy Outer Cylinder Tube, Semi-finished

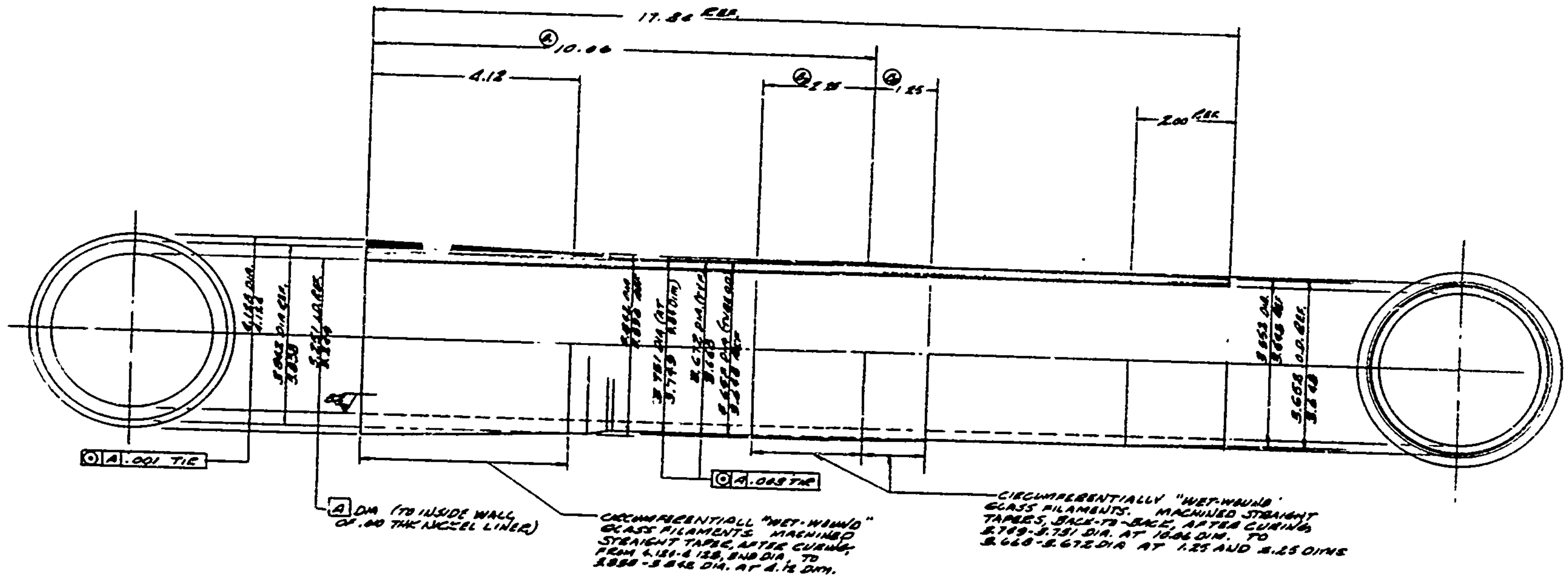



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Figure 5-84. Boron-Epoxy Outer Cylinder Tube With Glass Reinforcements

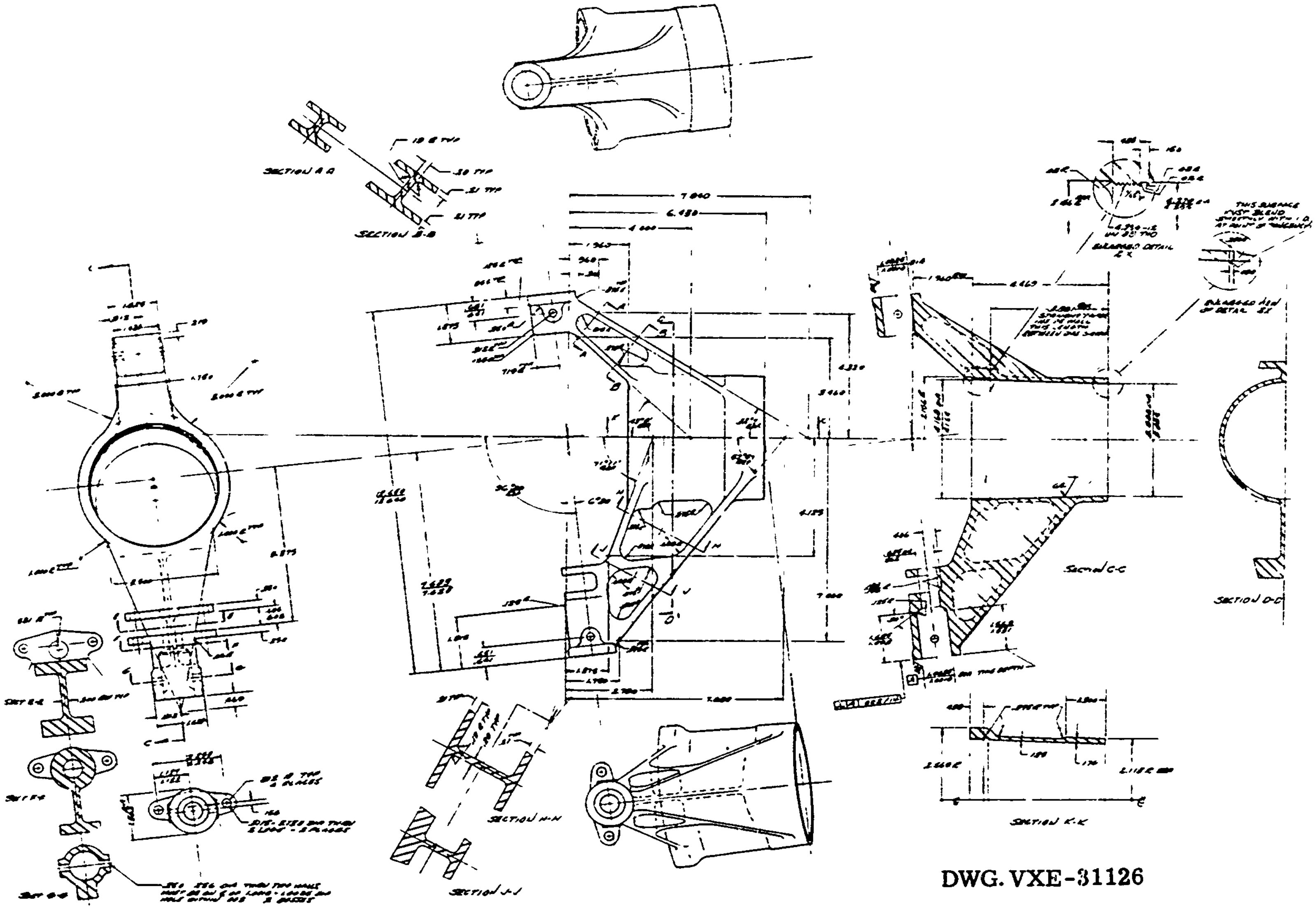


Figure 5-85. Outer Cylinder Trunnion Fitting

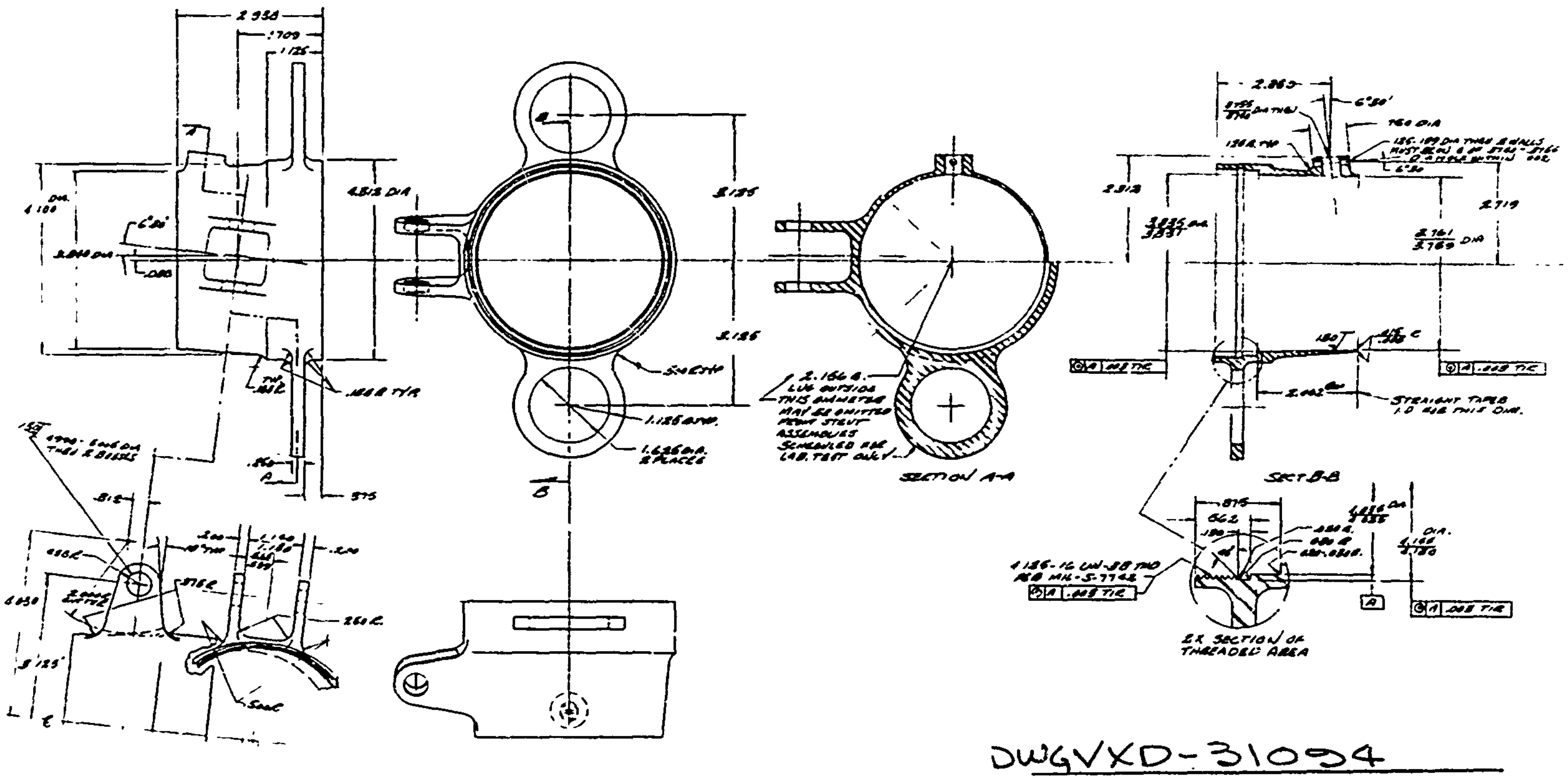


Figure 5-86. Side Brace Fitting

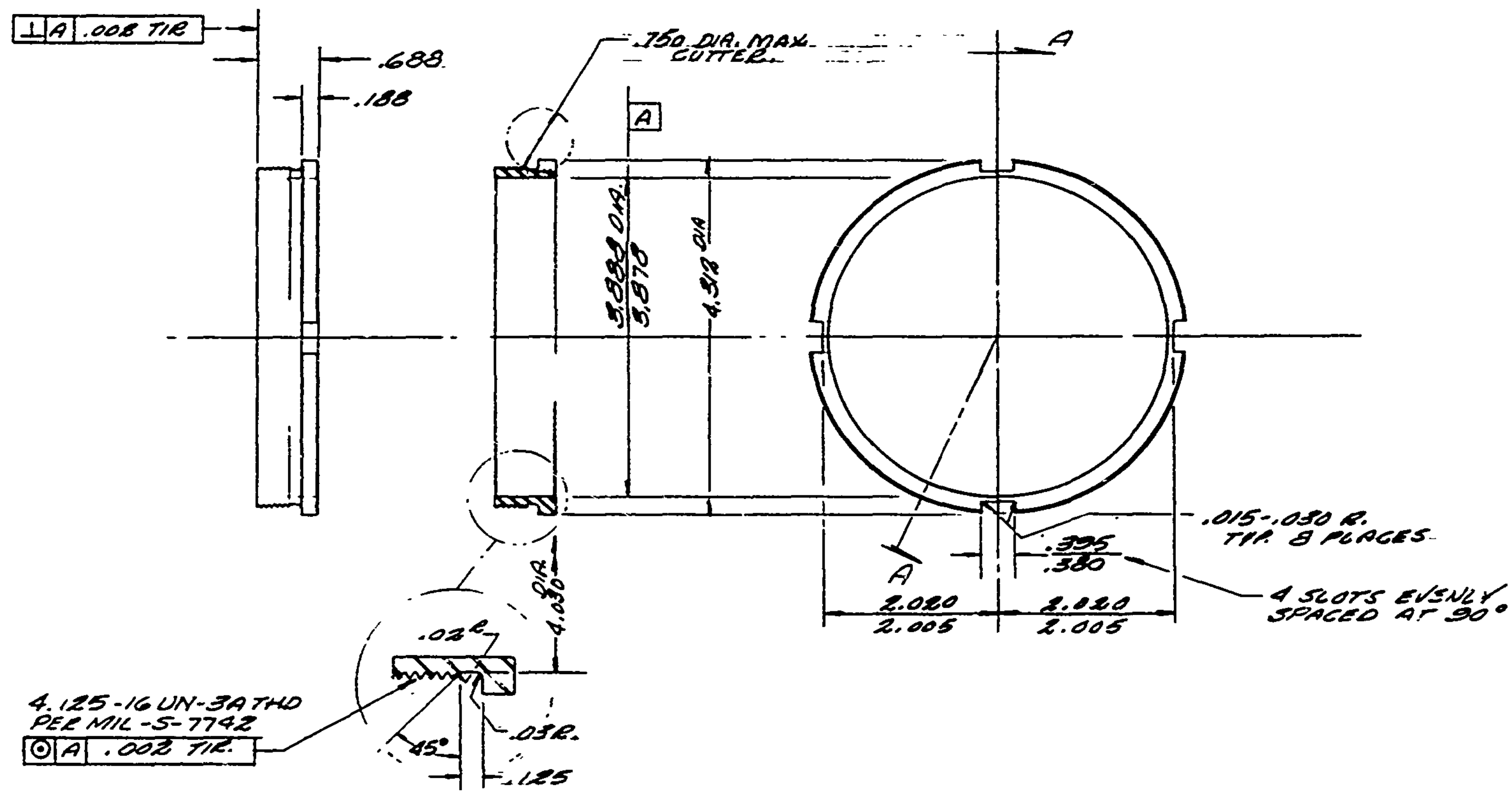


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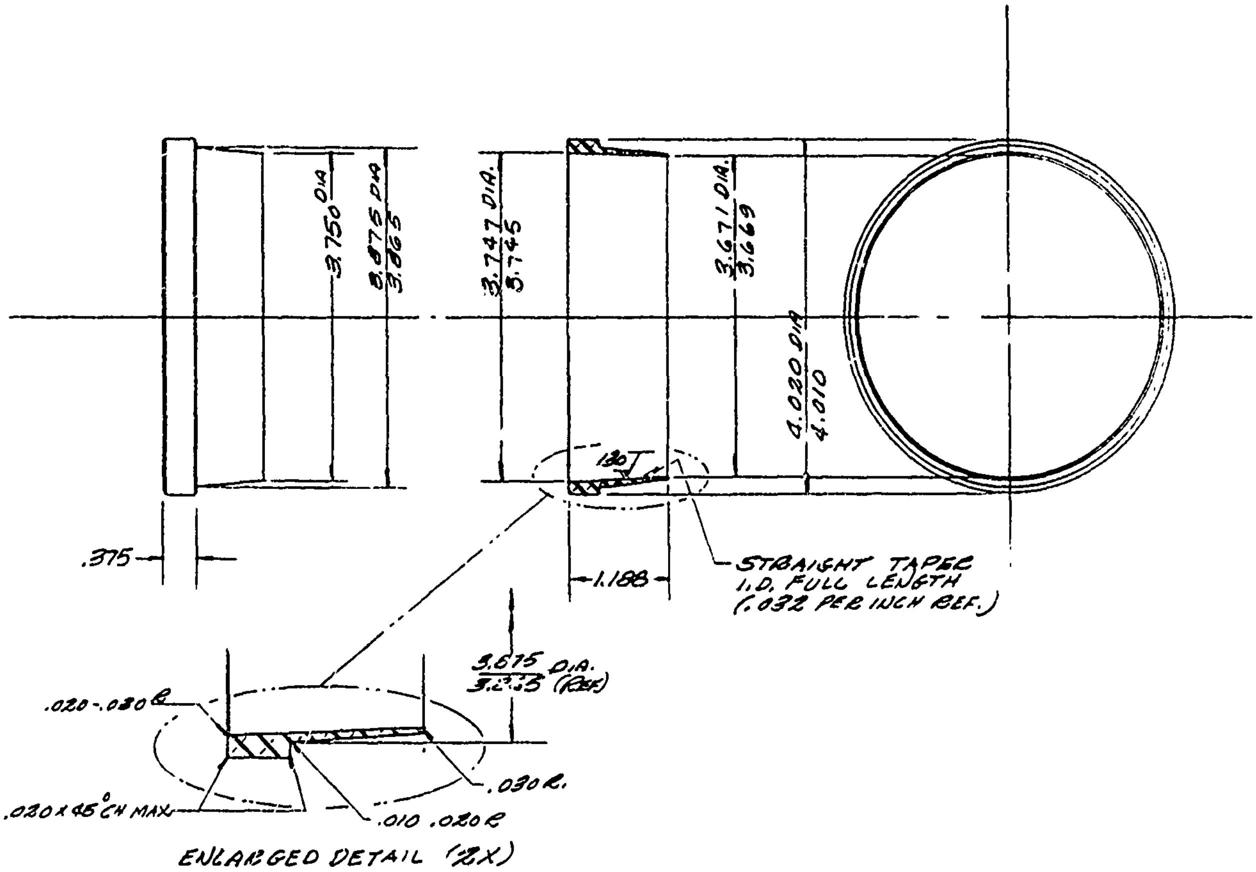
Figure 5-87. Side Brace Fitting




DWG. VXC-31096

Figure 5-88. Side Brace Fitting

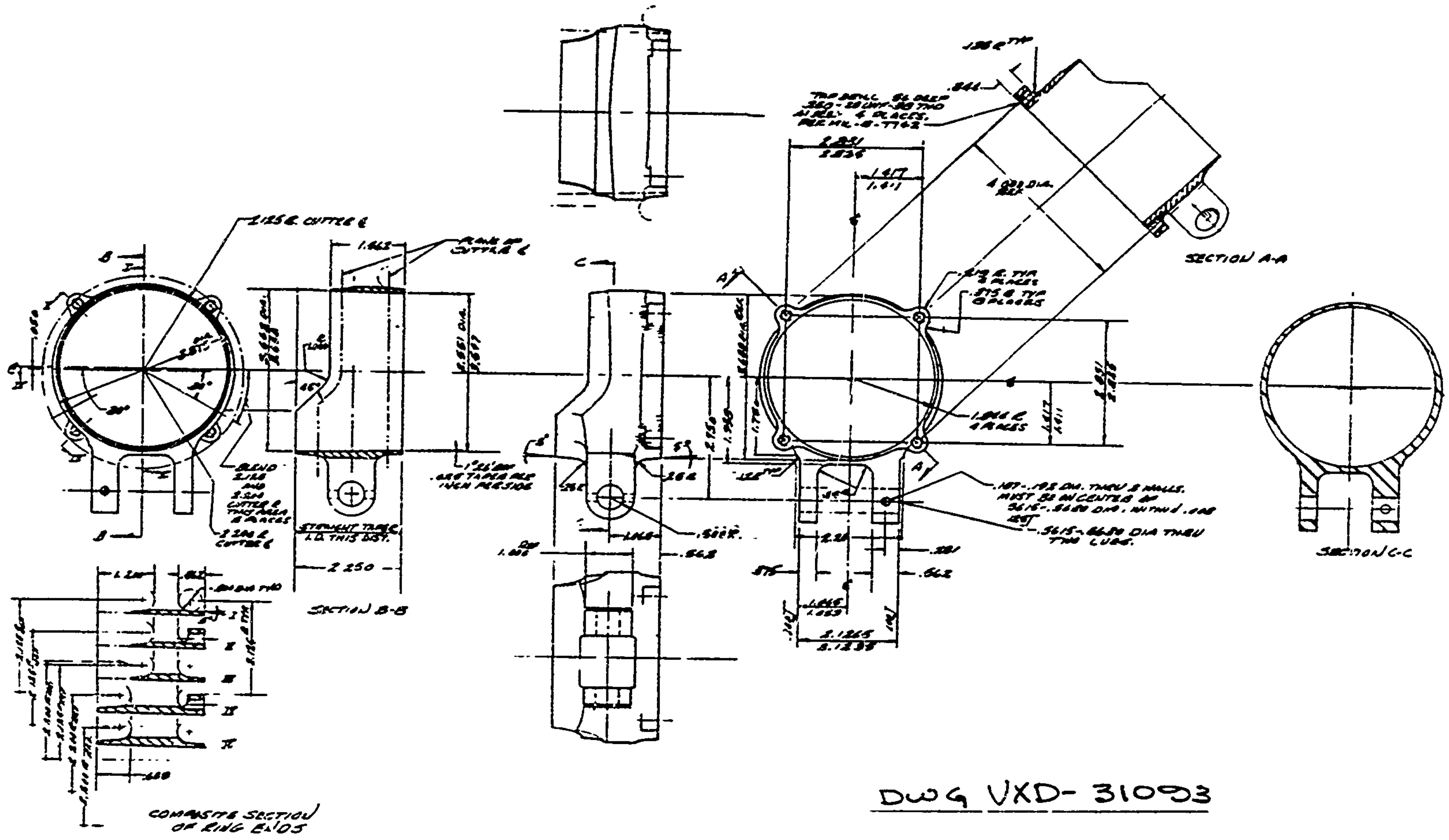



Figure 5-89. Torque Arm Fitting

5.3.1.4 Boron-Epoxy Piston-Axle

The prototype assembly design which evolved from the Phase I study is shown in Figure 5-90. This design concept was proven by the fabrication and test during Phase I of the trial specimen illustrated in Figure 5-95.

1. Prototype Assembly

The boron-epoxy piston and axle assembly proposed for fabrication in Phase II is illustrated in Figures 5-90 and 5-91. The basic structure consists of a boron composite cylinder socket joined to a high strength steel axle fitting.

Composite Cylinder -

The basic cylinder description including layup specifications is shown in Figure 5-92. A $0_2/\pm 45/90$ laminate pattern is employed at the upper end where the loading is primarily shear. In the main body of the cylinder a $0_4/90$ laminate pattern is required to resist loadings which are primarily bending and internal pressure. At the center, the metering pin diaphragm support ledge is formed from a 0, 90 layup pattern. At the lower end local wall reinforcement is required for the socket connection. This reinforcement relies heavily on $\pm 45°$ reinforcements to resist local wall shears arising from socket joint bearing forces induced by axle bending.

A nickel liner is applied to the inside surface to provide a wearing surface for the metering orifice diaphragm seal (Figure 5-92) and also to provide leakage resistance to internal fluid pressure. A nickel liner is also applied to the outside surface, also for leakage resistance, and to provide a hard wearing surface for the lower bearing, Figure 5-93.

Axle Fitting Attachment -

The axle-cylinder joint utilizes the same mechanical retention principle described for the outer cylinder-trunnion fitting attachment illustrated in Figure 5-80. The feasibility of applying this concept to the piston-axle design was established during fabrication and structural test trials of a simulated piston-axle specimen. The results of this test are reported below.

Stress Analysis -

Strength calculations associated with this component are given in Appendix D.

Fabrication -

The fabrication details for the piston assembly are described in Paragraph 8.2.6.2.

2. Trial Specimen - (Piston-Axle)

The piston-axle specimen illustrated in Figure 5-95 was designed to simulate the prototype piston-axle described in Figures 5-90 and 5-91.

The boron-epoxy cylinder was fabricated by Hercules and is described in Figure 5-96. The processing details concerning the fabrication of this piston specimen are given in Paragraph 8.2.6.1.

This cylinder, as delivered to Bendix, contained some interlaminar voids as indicated by the photographs of Figures 8-81 and 8-82. It was expected that these flaws would significantly affect the results of the structural test. However, it was decided to proceed with this particular specimen since time and cost limitations did not permit fabricating a second cylinder.

The remaining hardware was procured by Bendix from 220 ksi UTS steel. The various components were then assembled and tested in the Bendix structure laboratory. The test setup is shown in Figure 5-97.

The purpose of the structural test performed on this specimen was threefold.

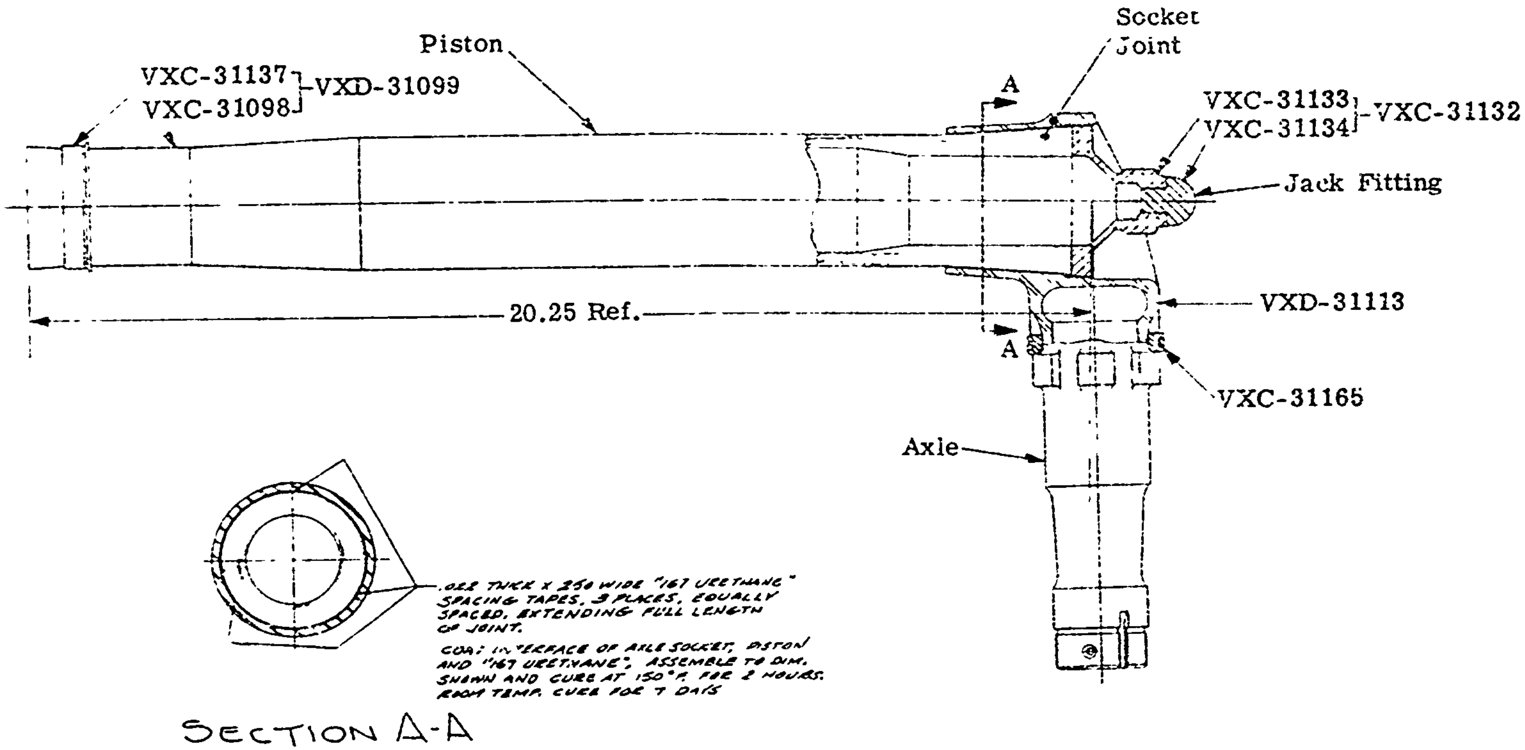
1. Confirm strength of axle-cylinder joint.

2. Check basic bending strength of composite cylinder.

3. Study punching effect of lower shock strut bearing on the composite cylinder.

A strength analysis indicated a rupture load capability for the setup of Figure 5-95 to be P = 14000 pounds. During test the load was increased in increments in the attempt to reach this load level. The specimen sustained a rupture at 9300 pounds or 67 percent of the target ultimate load. The rupture occurred at the edge of the 1.06-inch bearing pad, Figure 5-98.

The test fell somewhat short of the target load. However, the results were clouded by the rather severe delamination which existed in the composite cylinder. Nevertheless, the test was considered a success, since it provided an opportunity for Hercules to perform a fabrication trial from which techniques were derived aimed at producing on the next effort a cylinder of substantially improved quality. In addition since the specimen did successfully support a load of significant magnitude, the test results tend to confirm the structural integrity of the Bendix socket joint design.




Dwg. VXD-31131

Figure 5-90. Boron-Epoxy Piston and Axle Assembly (Proposed Design)

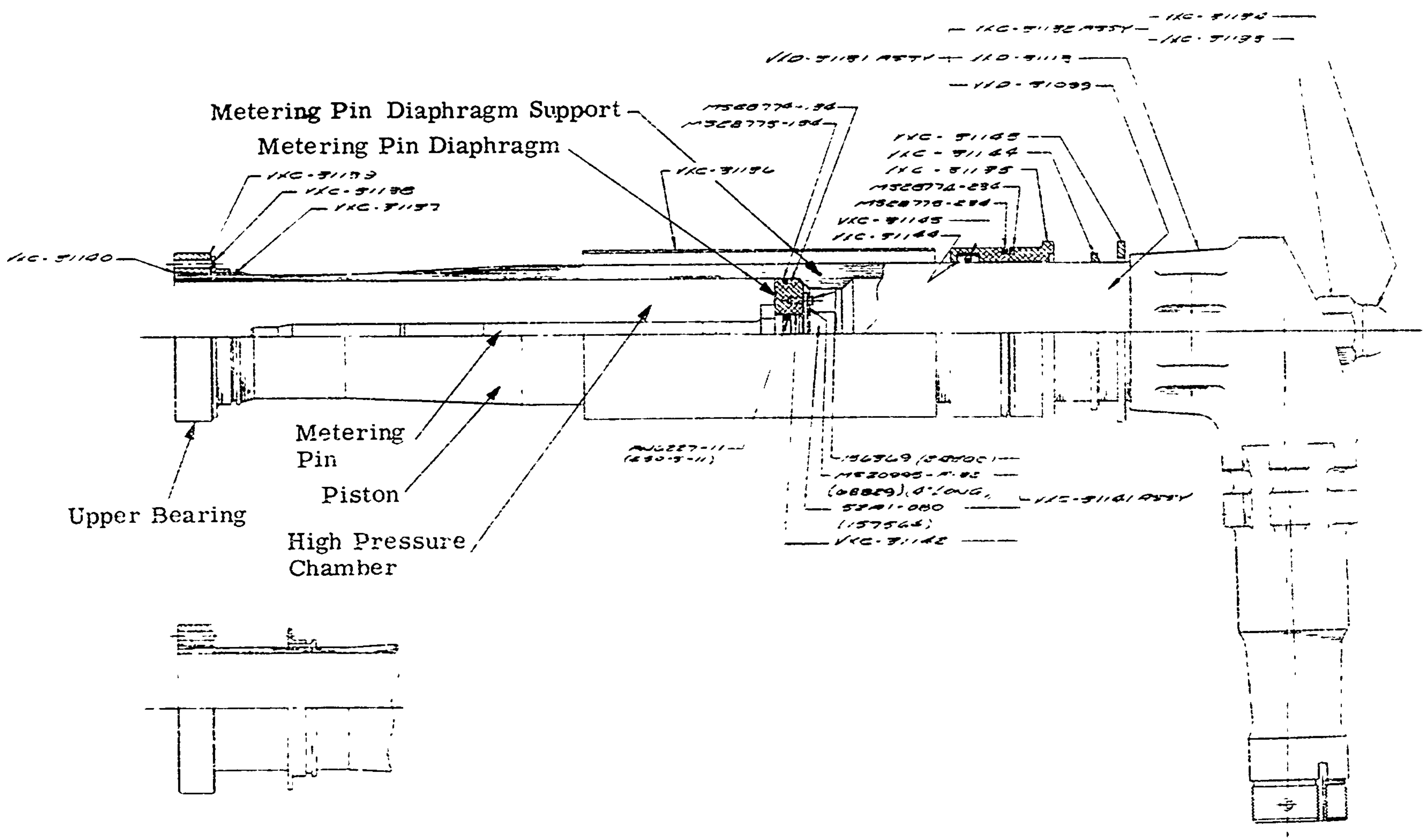
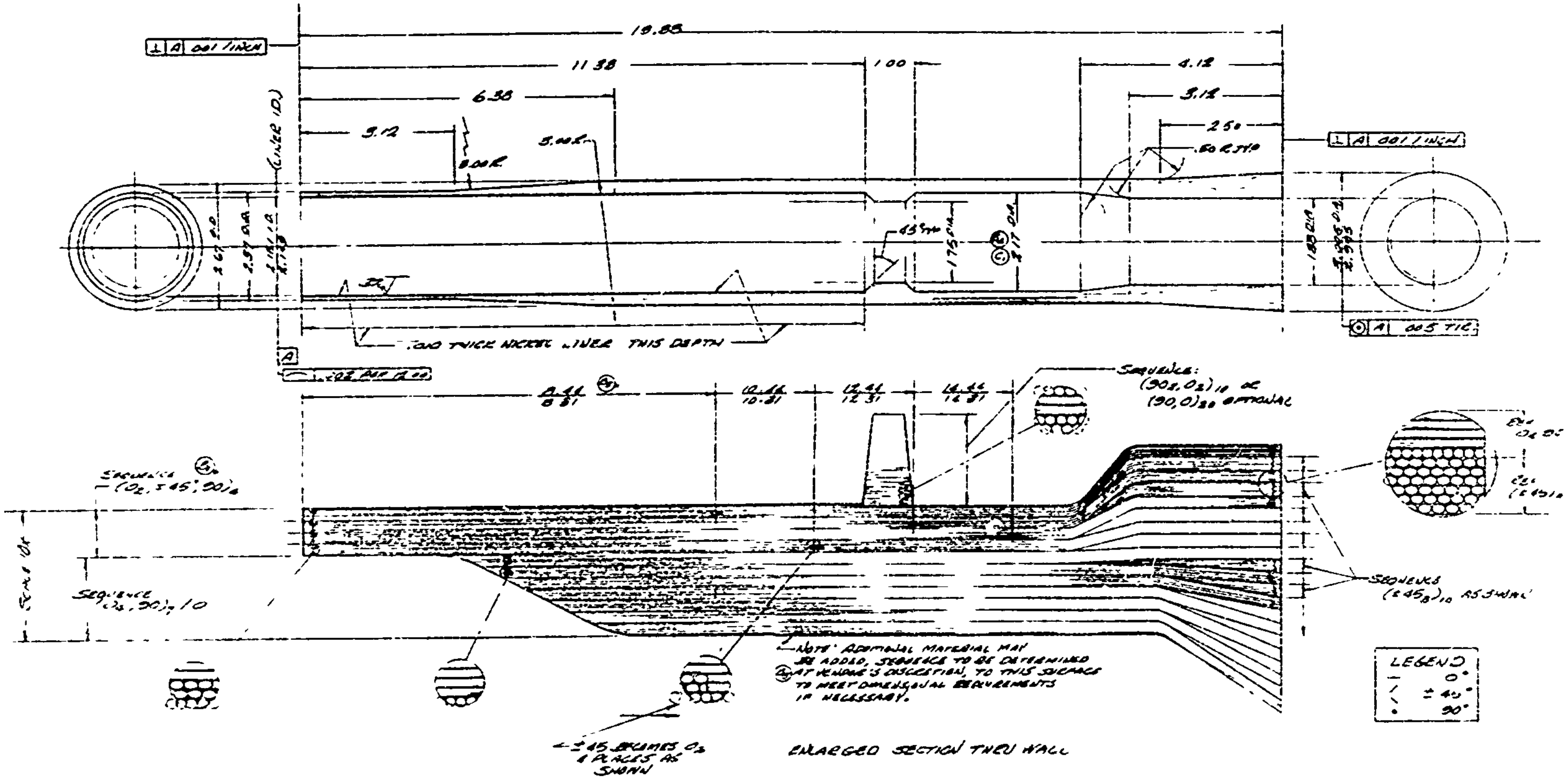
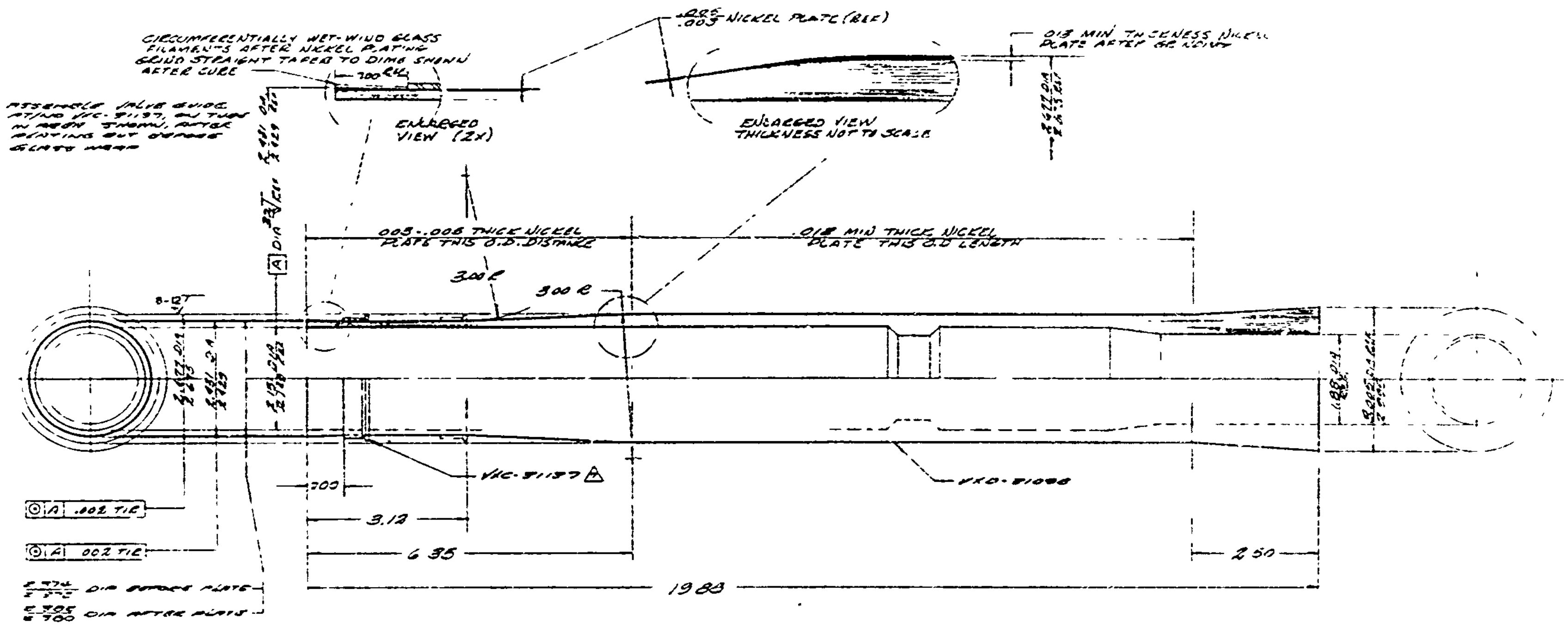



Figure 5-91. Boron-Epoxy Piston and Axle Assembly (Proposed Design)




DWG. VXD-31098

Figure 5-92. Boron-Epoxy Piston Cylinder (Proposed Design)




DWG. VXD-31099

Figure 5-93. Boron-Epoxy Piston Cylinder (Proposed Design)

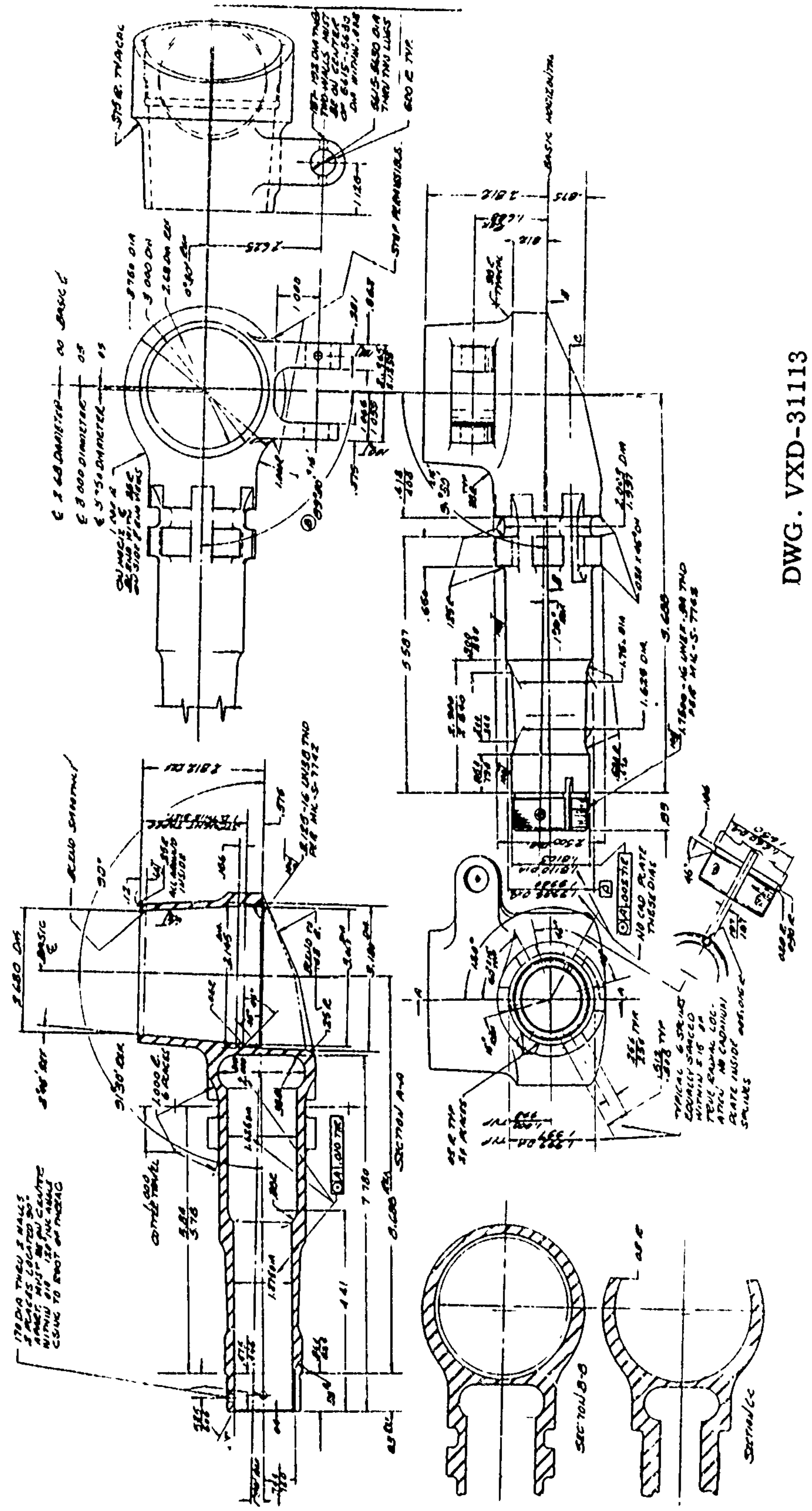


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Figure 5-94. Axle Fitting

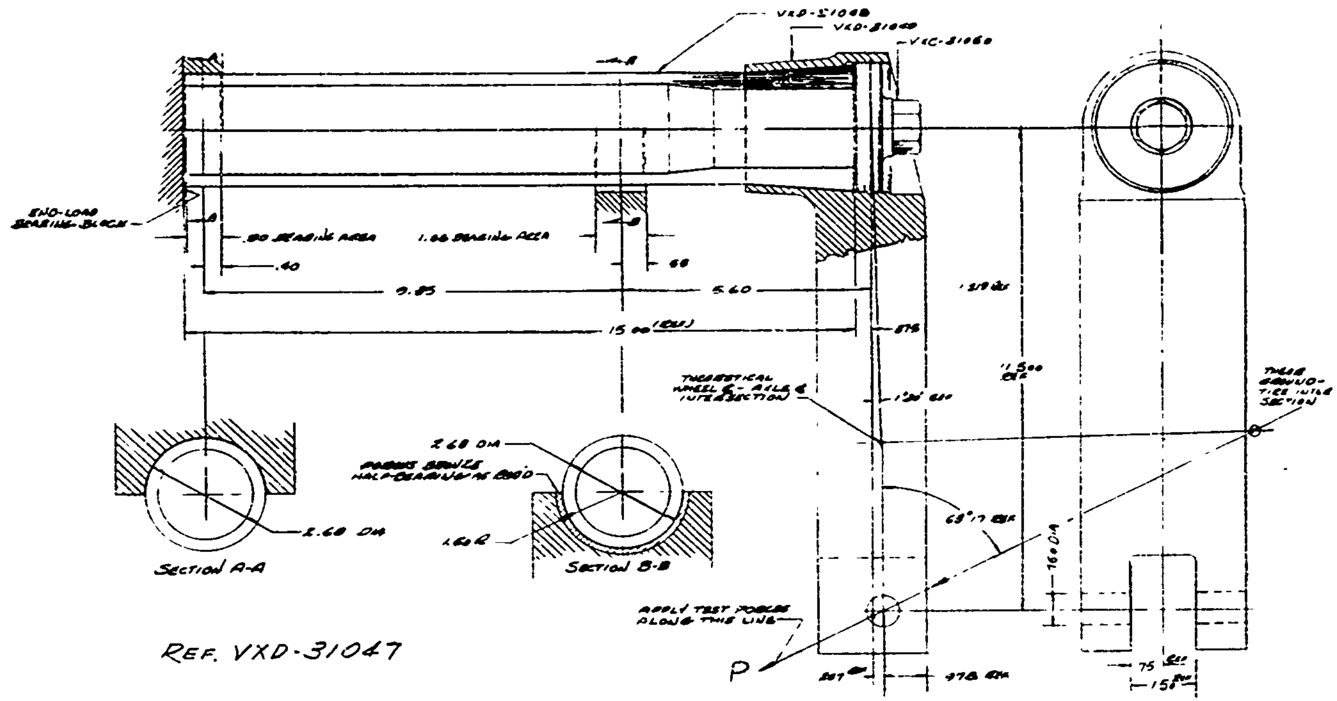
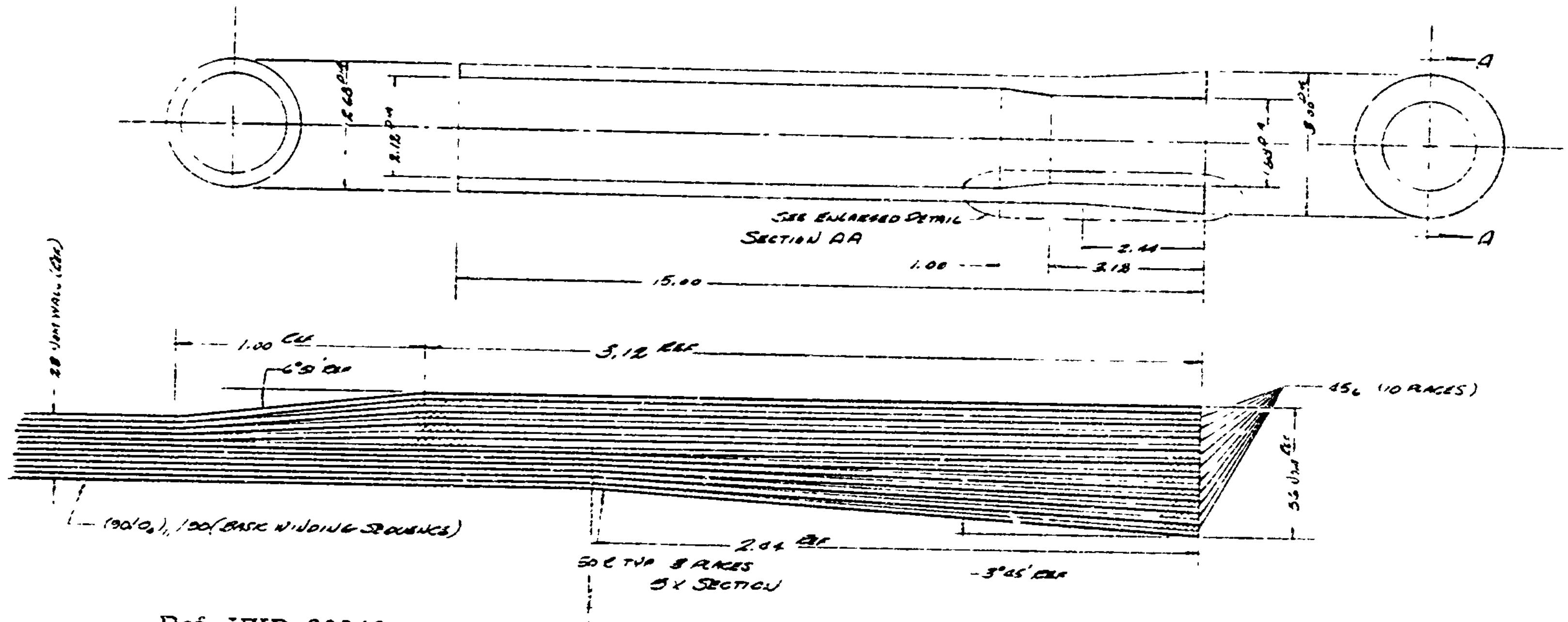



Figure 5-95. Boron-Epoxy Piston Specimen




Ref. VXD-31048

Figure 5-96. Cylinder for Boron-Epoxy Piston Specimen

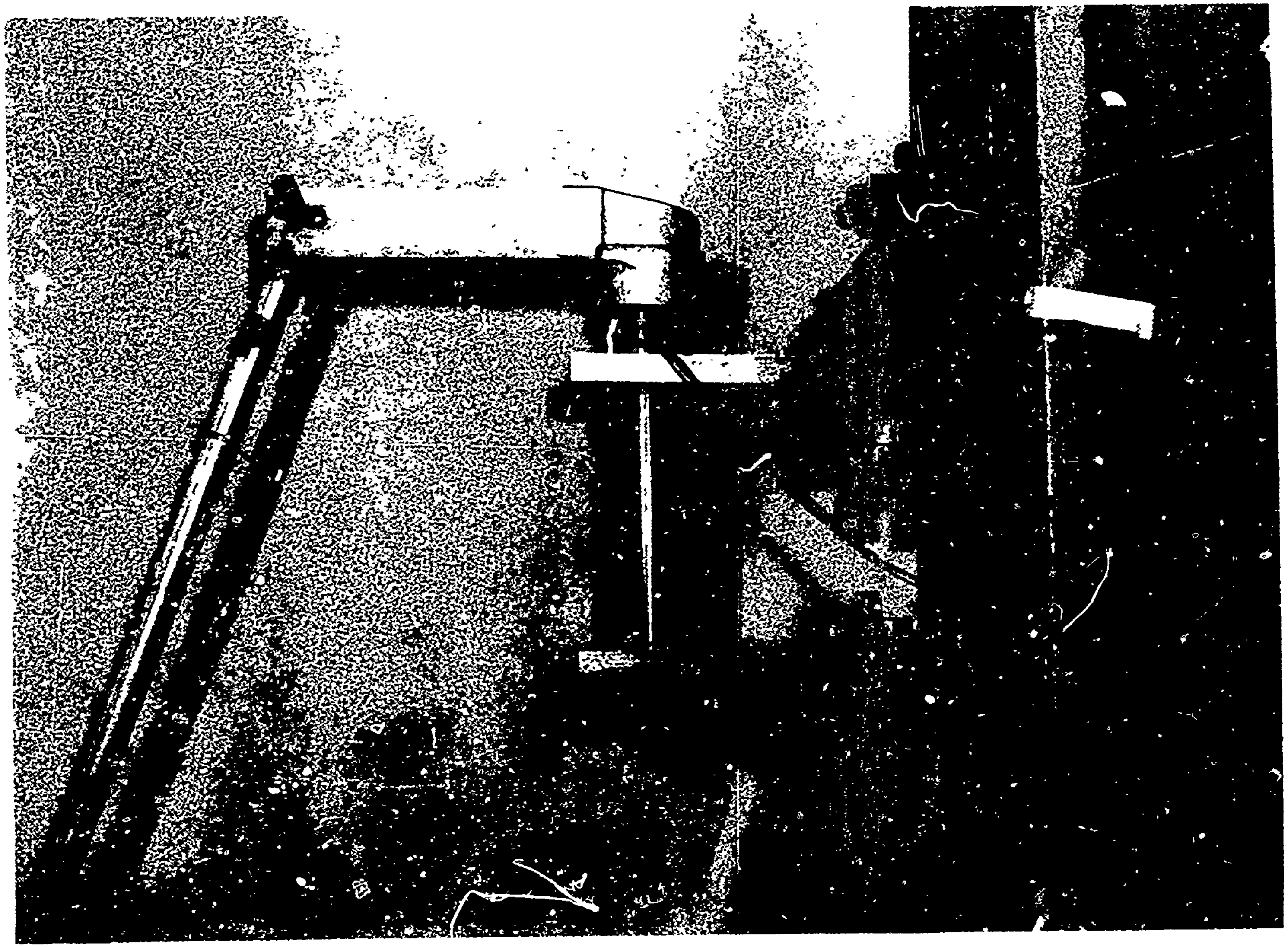


Figure 5-97. Test Setup for Piston Axle Specimen

Figure 5-98. Failed Piston Cylinder

### 5.3.1.5 Metallic Liner Characteristics

Some years prior to the start of this present effort, the AF Flight Dynamics Laboratory engaged in a study to provide a liner for landing gear filament composite shock absorber cylinders. This feasibility study indicated that a nickel liner could be utilized with boron-epoxy composite cylinders. Quantitative data were not available for adhesion, wear rate, porosity, friction, etc., and a program was initiated to design, fabricate, and test boron-epoxy cylinders with nickel liners. This effort was specifically aimed at providing data for the A-37B landing gear. A contract was issued to McDonnell-Douglas (F33(616)-68-C-1733) for the design and fabrication of six full size test cylinders. The testing was performed in the structures laboratory at WPAFB. The tests were designed to simulate the operating conditions to which the A-37B outer cylinder and liner assembly would be subjected during normal operation. These tests consisted of applying a combination of loads to a simulated piston stroking at varying internal hydraulic pressures. During these tests the nickel liners appeared to perform satisfactorily. As a result, it was recommended that the composite shock absorber cylinders for the A-37B landing gear incorporate 0.010 inch thick nickel liners.

The liners used on the McDonnell-Douglas cylinders were deposited by Electroforms, Inc. of Gardena, California. Bendix elected to use Electroforms as the source for liners on this program. The processing details described in Paragraph 8.2.7 were supplied by this firm. Also Reference 21 was given as a source for further information.

Nickel liners were specified for the inside surface of the outer cylinder, Figure 5-80 and for both the inside and outside surfaces of the piston, Figures 5-92 and 5-93.

## SECTION VI

## PROPOSED LANDING GEAR ASSEMBLIES

### 6.0 INTRODUCTION

This section describes both the BORSIC-aluminum and boron-epoxy landing gear assemblies proposed to the Air Force as designs feasible for Phase II fabrication. A summary of the weights analysis is also included.

The designs selected by the Air Force for Phase II fabrication are summarized. The completely fabricated filament composite assemblies ready for testing are illustrated.

### 6.1 SUMMARY OF PROPOSED PHASE I DESIGNS

As a result of the Phase I design activity, Bendix submitted for Air Force consideration the feasible designs indicated in Table 6-1. The design details associated with these concepts are discussed in Section V of this report. A parts list covering each assembly is contained in Appendix H.

The landing gear assemblies to be fabricated and tested in Phase II were to be made up from some combination of the components listed in Table 6-1. The specific components, BORSIC-aluminum or boron-epoxy, for the side brace and torque arms were to be selected by the Air Force during the final Phase I review.

TABLE 6-1. PHASE I DESIGN SUMMARY

<table>
<tr><th rowspan="2"></th><th colspan="2">BORSIC-Aluminum</th><th colspan="2">Boron-Epoxy</th></tr>
<tr><th>Components</th><th>Assembly</th><th>Components</th><th>Assembly</th></tr>
<tr><td>Side Brace</td><td>Figure 5-8<br>Figure 5-9</td><td>Figure 5-7<br>Figure 6-1</td><td>Figure 5-36<br>Figure 5-37</td><td>Figure 5-35<br>Figure 6-3</td></tr>
<tr><td>Torque Arms</td><td>Figure 5-33</td><td>Figure 6-2</td><td>Figure 5-55</td><td>Figure 6-4</td></tr>
<tr><td>Outer Cylinder-Trunnion</td><td></td><td></td><td>Figure 5-80</td><td rowspan="2">Figure 6-5<br>Figure 6-6<br>Figure 6-7</td></tr>
<tr><td>Piston-Axle</td><td></td><td></td><td>Figure 5-91</td></tr>
</table>

## 6.2 WEIGHT SUMMARY

A weight analysis of the components proposed for Phase II fabrication resulted in the summary given below in Tables 6-2 and 6-3. See discussion following.

TABLE 6-2. ASSEMBLY WEIGHTS

| | Existing | | Boron-Epoxy | | | BORSIC-Aluminum | | |
|---|---|---|---|---|---|---|---|---|
| Assembly | Figure | Weight Lbs. | Figure | Weight Lbs. | R % | Figure | Weight Lbs. | R % |
| Torque Arm | 5-5 | *2.93 | 6-4 | 1.97 | 33 | 6-2 | 2.10 | 28 |
| Side Brace | 5-1 | *3.39 | 6-3 | 2.84<br>*2.67 | 16<br>21 | 6-1 | 3.19 | 6 |
| Shock Absorber | 5-6 | *37.23 | 6-5 | 31.39<br>*33.00 | 16<br>*13 | | | |

*Measured weights - All others calculated.

TABLE 6-3. COMPONENT WEIGHTS

| | Existing | | Boron-Epoxy | | | BORSIC-Aluminum | | |
|---|---|---|---|---|---|---|---|---|
| Component | Figure | Weight Lbs. | Figure | Weight Lbs. | R % | Figure | Weight Lbs. | R % |
| Torque Arm | 5-2 | *1.16 | 5-55 | 0.69 | 40 | 5-33 | 0.75 | 35 |
| Side Brace Upper | 5-1 | *0.83 | 5-37 | 0.67<br>*0.63 | 19<br>24 | 5-22 | 1.63 | 2 |
| Side Brace Lower | 5-1 | *0.91 | 5-36 | 0.67<br>*0.67 | 27<br>27 | 5-21 | 0.73 | 20 |
| Outer Cylinder - Trunnion | 5-3 | *18.71 | 5-80 | 15.73<br>*15.78 | 16<br>16 | | | |
| Piston-Axle | **5-4 | *12.21 | 5-90 | 8.70<br>*9.93 | 29<br>19 | | | |

*Measured weights. All others calculated.
**Less metering pin, metering pin support, upper bearing.

In Tables 6-2 and 6-3 a comparison is given between the weights of the proposed composite components and the existing conventional metallic design. The tables refer to the figure numbers in this report which illustrate the assembly or component on which the particular weight is based. Numbers prefixed by an asterisk represent weights measured from actual parts while the others were computed from detailed drawings. The weights for the boron-epoxy items were measured from parts fabricated during Phase II activities.

It may be noted that in every case a weight saving maybe achieved by replacing the existing steel or aluminum components with the filament composite designs. The value R indicates the weight savings in percent of the existing metal component.

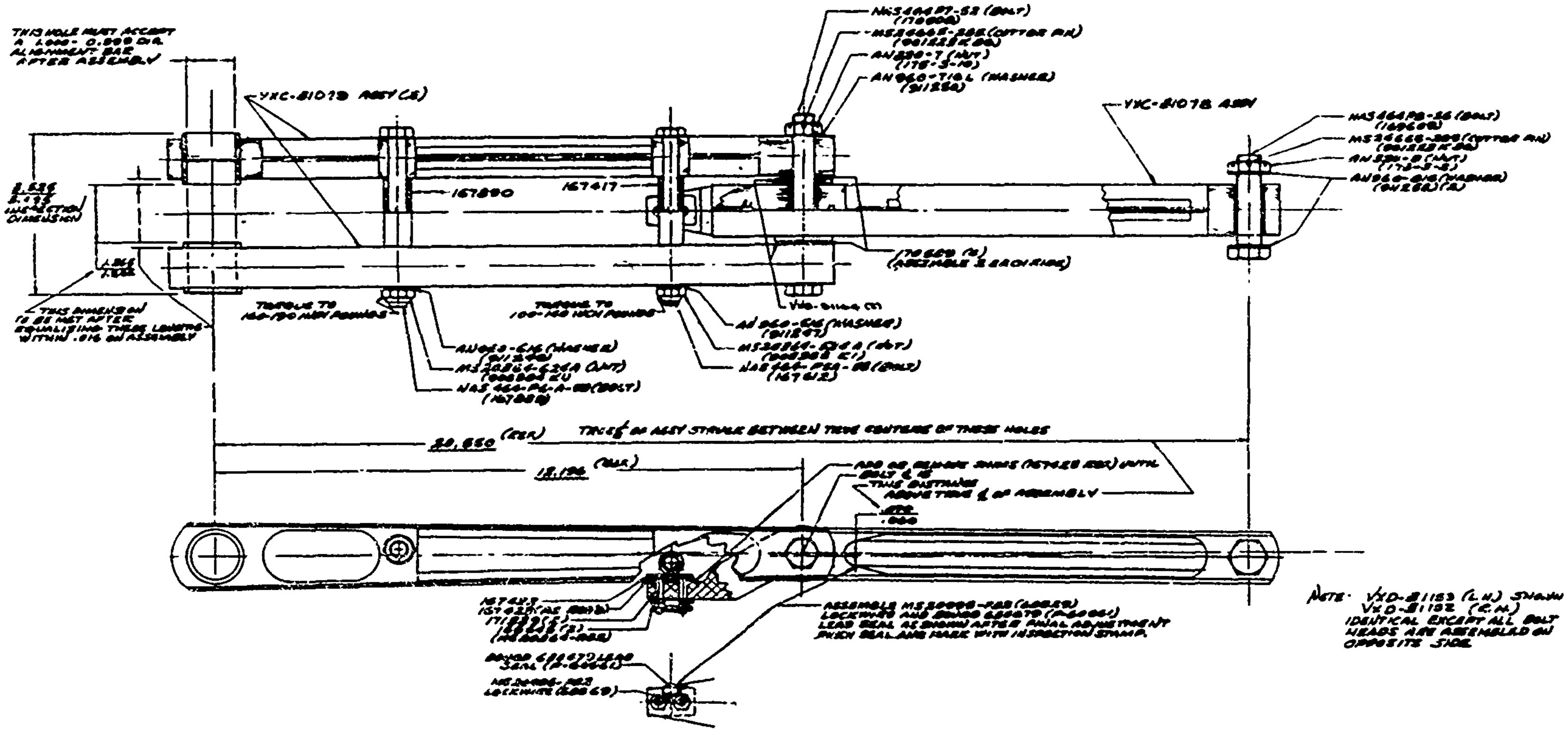
These weight values of Table 6-2 represent the entire assembly indicated in the column headed "Figure" which includes the weight of many fittings fabricated from conventional materials. The weight saving in terms of the basic filament component by itself is even greater. The summary in these terms is given in Table 6-3.

It may be noted that the weights of the current metallic parts reflect a fairly detailed knowledge of materials properties, design and analytical techniques, and fabrication experience, gained from many years of experience with this type of product. Hence the metallic component designs may be considered to be reasonably optimum. When a similar degree of knowledge and experience is accumulated and applied to filament composite products, particularly with respect to fitting design and fabrication techniques, it may be expected that even greater weight savings will be achieved from the production of landing gear parts from filament composite materials.

## 6.3 RESULTS OF AIR FORCE REVIEW

The results of the Phase I work were presented by Bendix and its subcontractors to the Air Force during a program review held at the Flight Dynamics Laboratory in December, 1970. After evaluating the data presented, the Air Force authorized the building and testing of a landing gear assembly comprising a piston, outer cylinder and side brace fabricated from boron-epoxy composites and the steel torque arms currently being furnished for the conventional A-37B main landing gear. These items are summarized below.

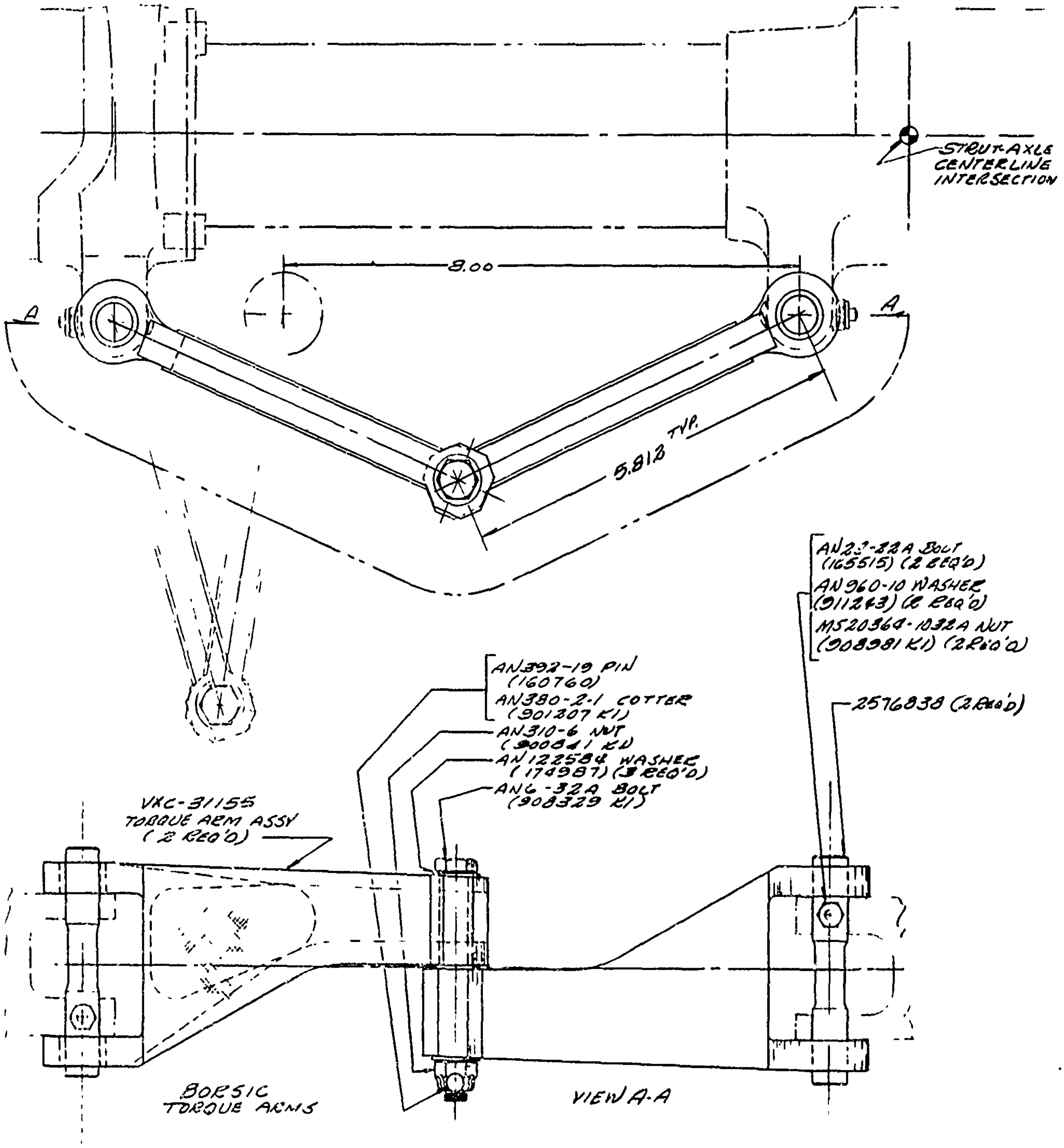
| | |
|---|---|
| Side Brace | Figure 6-3 |
| Torque Arm | Figure 6-8 |
| Outer Cylinder | Figure 5-80 |
| Piston | Figure 5-91 |
| Shock Absorber | Figure 6-5 |



DWG. VXD-31153

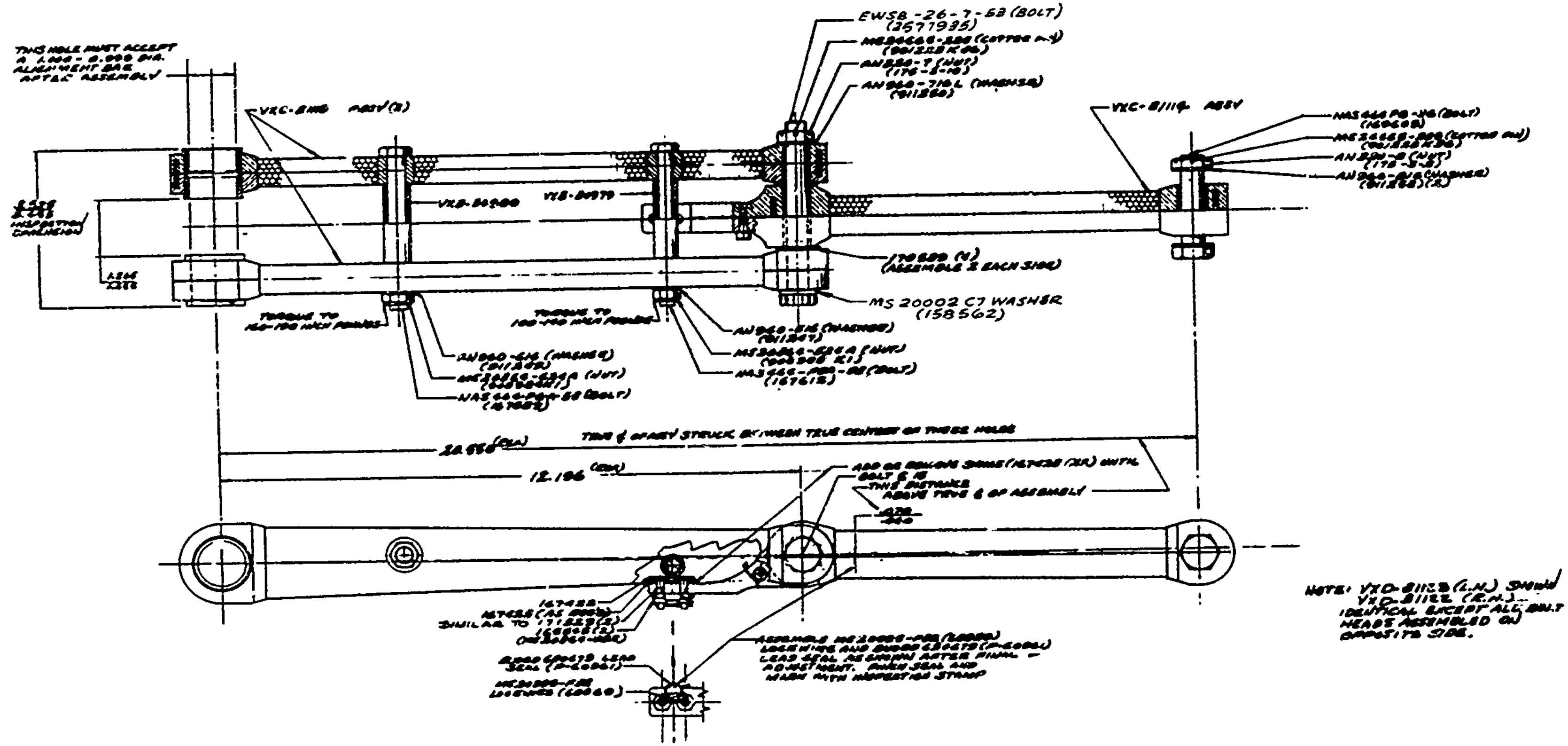
(Same as figure 5-7)

Figure 6-1. Side Brace Assembly, Final, BORSIC-Aluminum (Proposed Design)



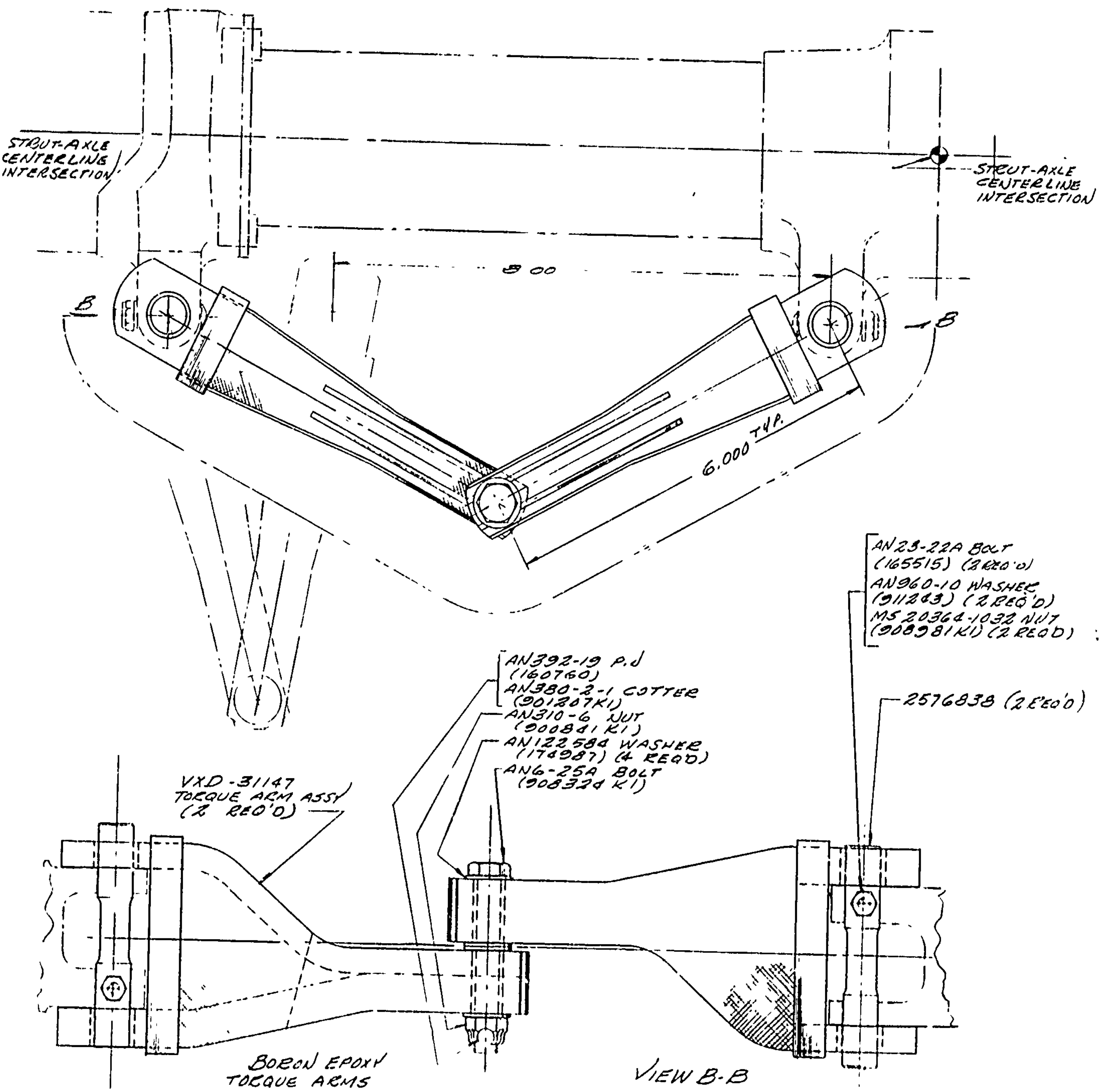

DWG. VXR-31046 SH 2

Figure 6-2. BORSIC-Aluminum Torque Arm Assembly (Proposed Design)




DWG. VXD-31123
(Same as Figure 5-35)

Figure 6-3. Side Brace Assembly, Final, Boron-Epoxy (Proposed Design)




DWG. VXR-31046 SH 2

Figure 6-4. Boron-Epoxy Torque Arm Assembly (Proposed Design)

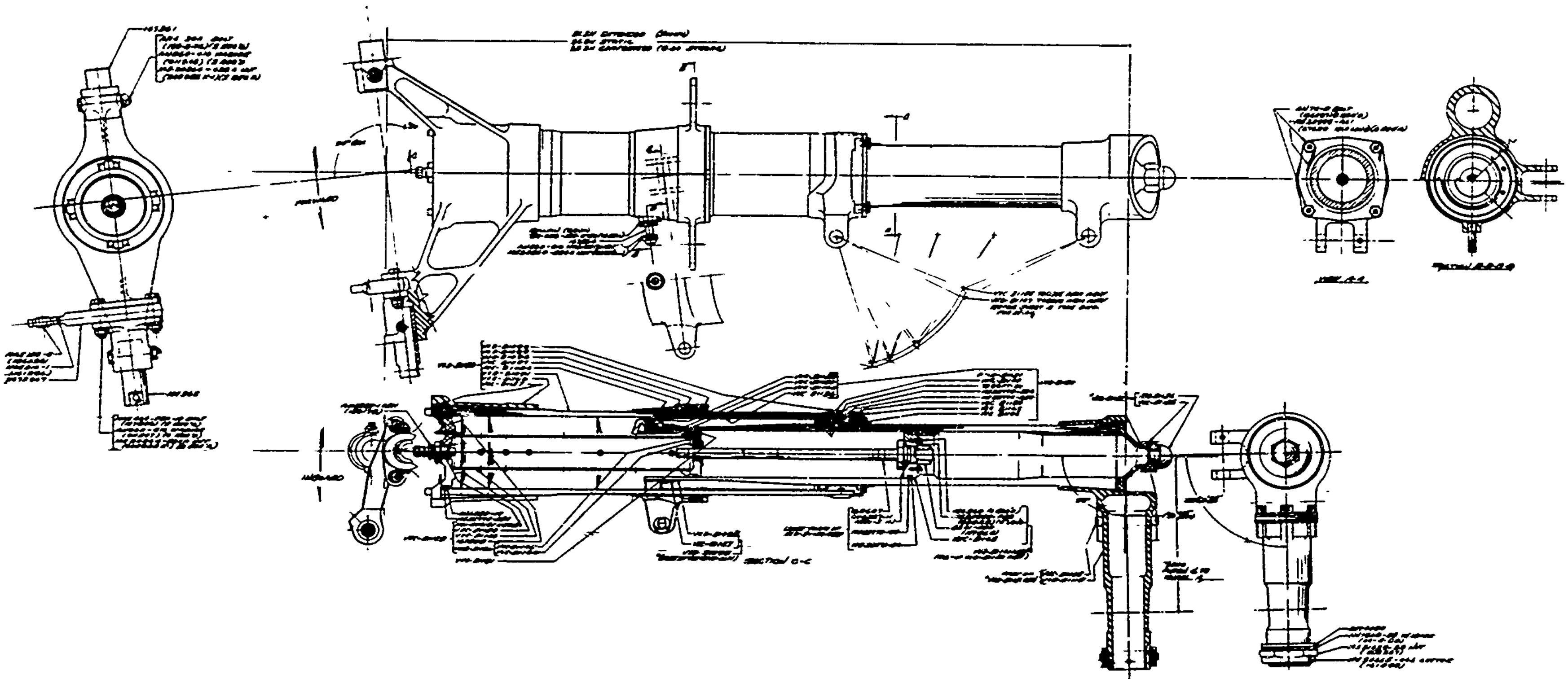
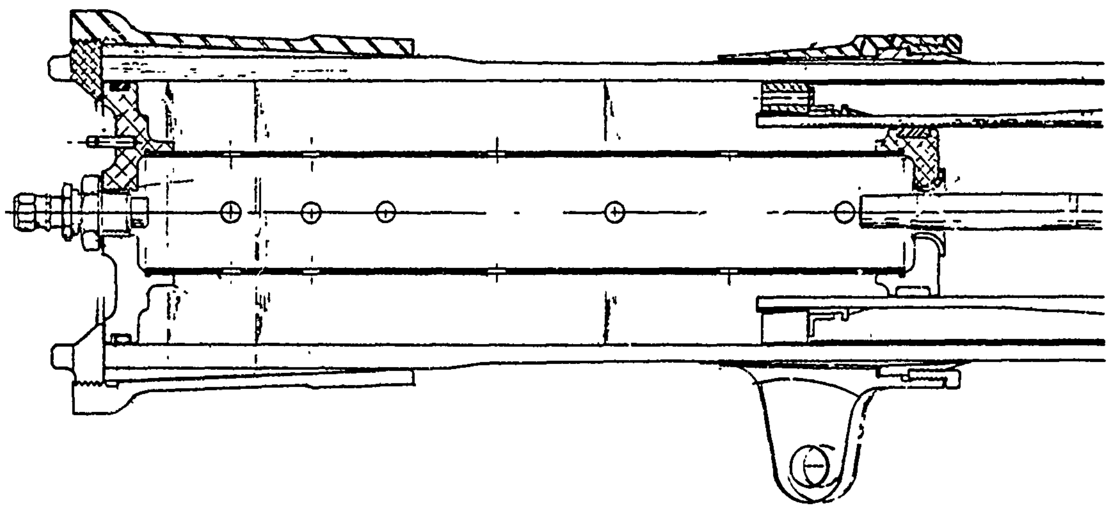



Figure 6-5. Boron-Epoxy Shock Absorber Assembly

UPPER SECTION
(Ref. Figure 6-5)



CENTER SECTION
(Ref. Figure 6-5)

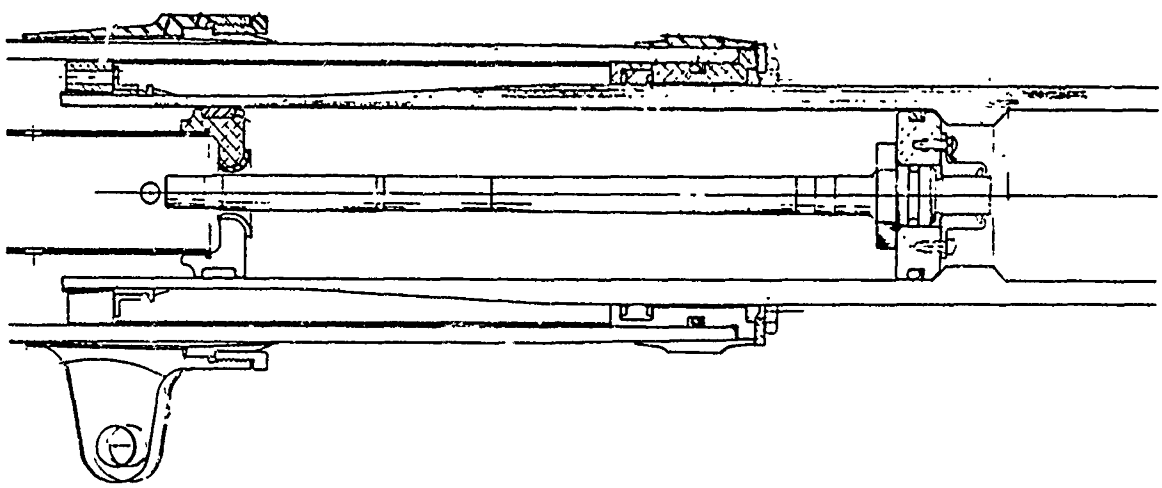
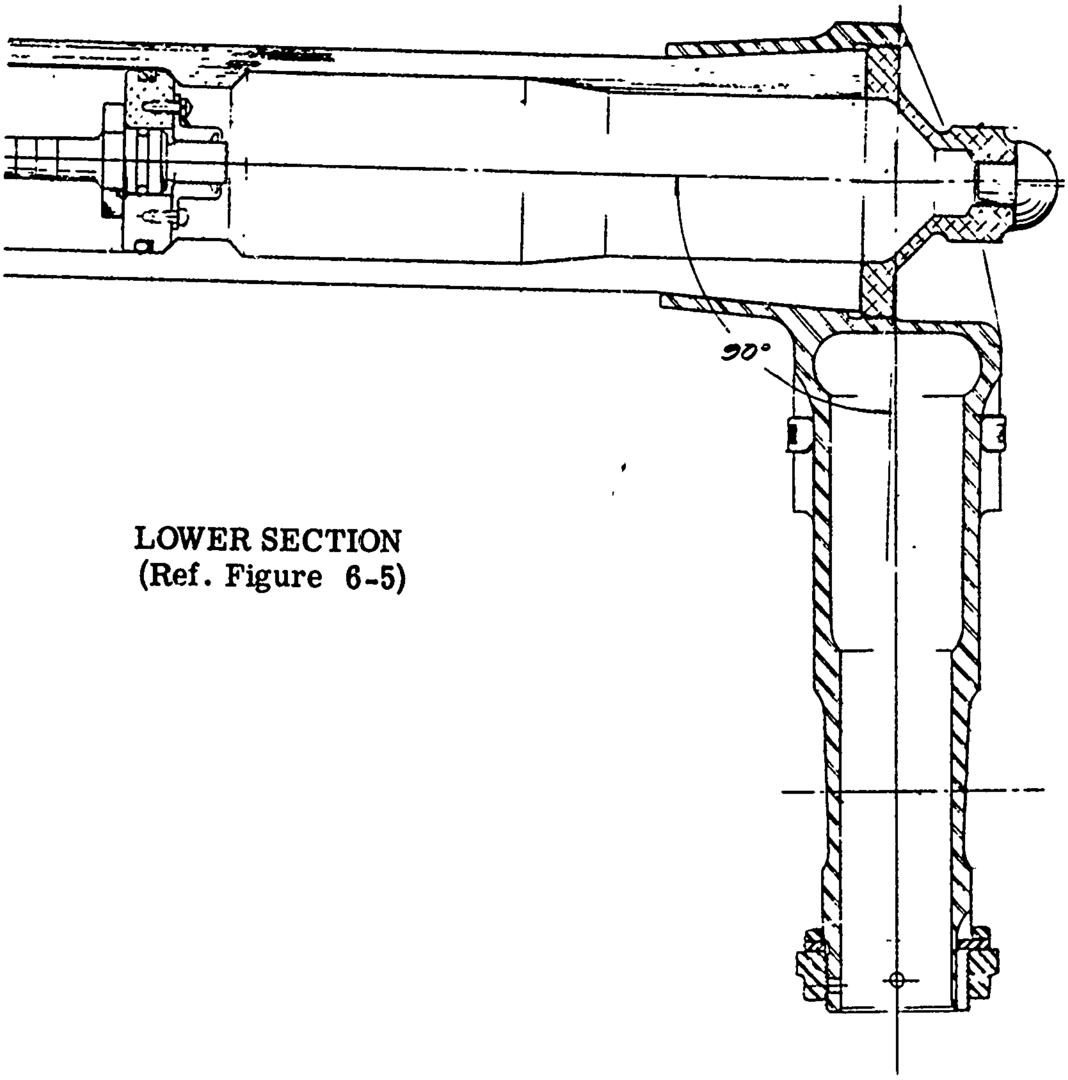


Figure 6-6. Enlarged Views of Shock Absorber Assembly




LOWER SECTION
(Ref. Figure 6-5)

Figure 6-7. Enlarged View of Shock Absorber Assembly

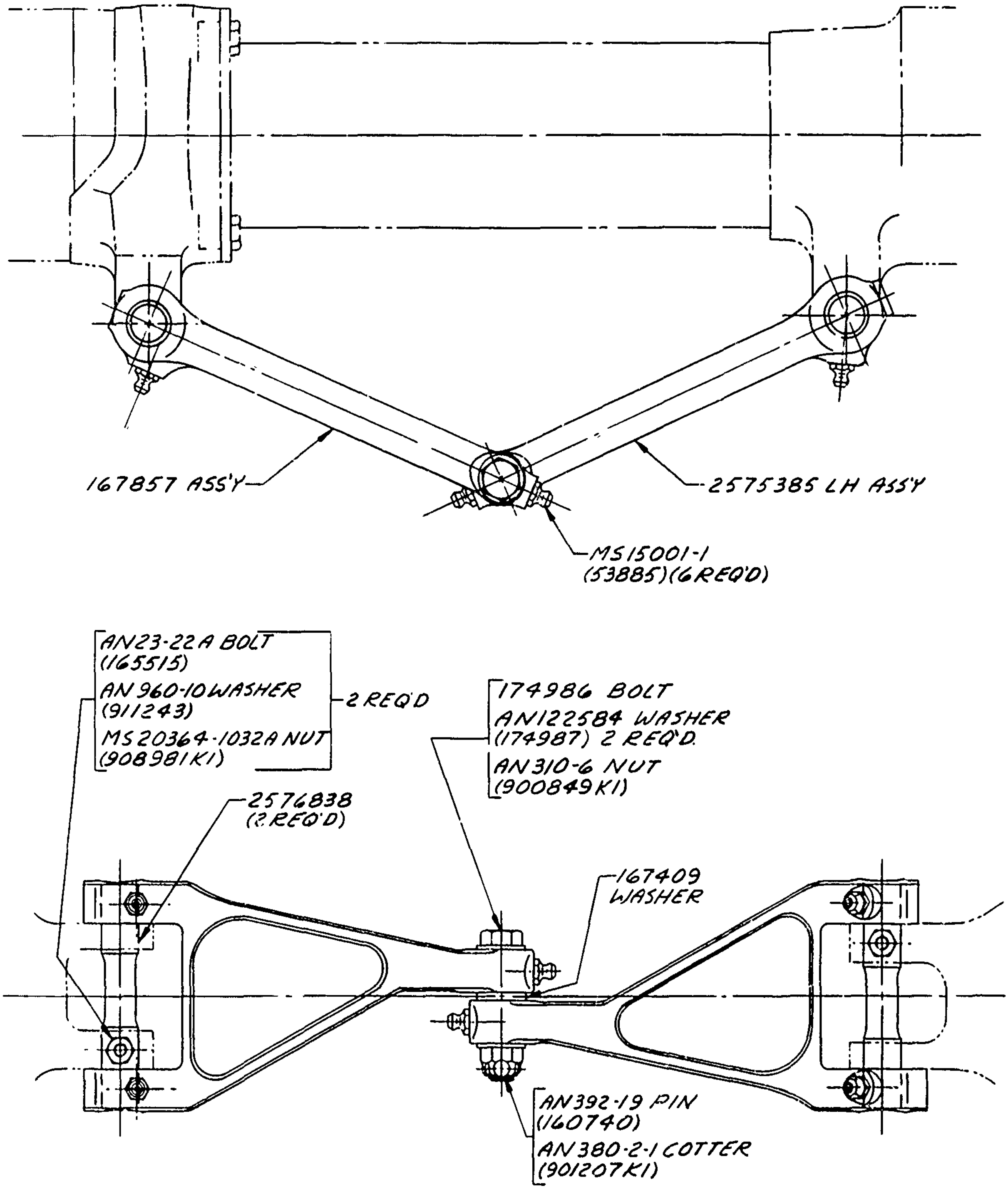



Figure 6-8. Steel Torque Arm Assembly

## 6.4 REDESIGN OF METALLIC HARDWARE FOR TEST VERSION

The version of the shock absorber assembly design, Figure 6-5, approved by the Air Force includes a number of metallic (noncomposite) hardware items. Some of these items perform functions necessary to the operation of the aircraft but have no influence in the structural or mechanical performance of the composite components. In addition there are hardware items involving machined contours intended primarily for weight saving purposes which again have no influence on the composite components. To include these items in the test assemblies would merely add to fabrication costs and would in no way affect the performance of the gear assembly. As a cost saving measure a simplified version of the gear assembly excluding these features was fabricated and tested.

The test version of the assembly is shown in Figure 6-9. The simplifications incorporated in the test version are itemized below. The differences between the aircraft and test versions may be determined by comparing the assemblies of Figures 6-9 and 6-10 in the regions of the circled numbers which correspond to those in the listing below.

SIMPLIFICATIONS

1. Trunnion sockets - Weight saving contours eliminated.
2. Retraction lever - Lever arm deleted. Lever attachment lugs on trunnion arm omitted.
3. Trunnion arm - Weight saving cavity between flanges omitted.
4. Uplock stud - Pin and socket omitted.
5. Aircraft tiedown rings - Deleted.
6. Combination jacking point and cylinder retainer - Light weight version replaced by test version used in Phase I specimen.

A parts list encompassing the test version of the landing gear assembly is included in Appendix I.

## 6.5 PHASE II PROTOTYPE FABRICATION

The prototype components were fabricated according to the processing details described in the following paragraphs of this report.

| | | |
|---|---|---|
| Side brace | - | Paragraph 8.2.3.2 |
| Outer cylinder | - | Paragraph 8.2.5.2 |
| Piston | - | Paragraph 8.2.6.2 |

The finished components and assemblies are illustrated in Figures 6-11 and 6-12.

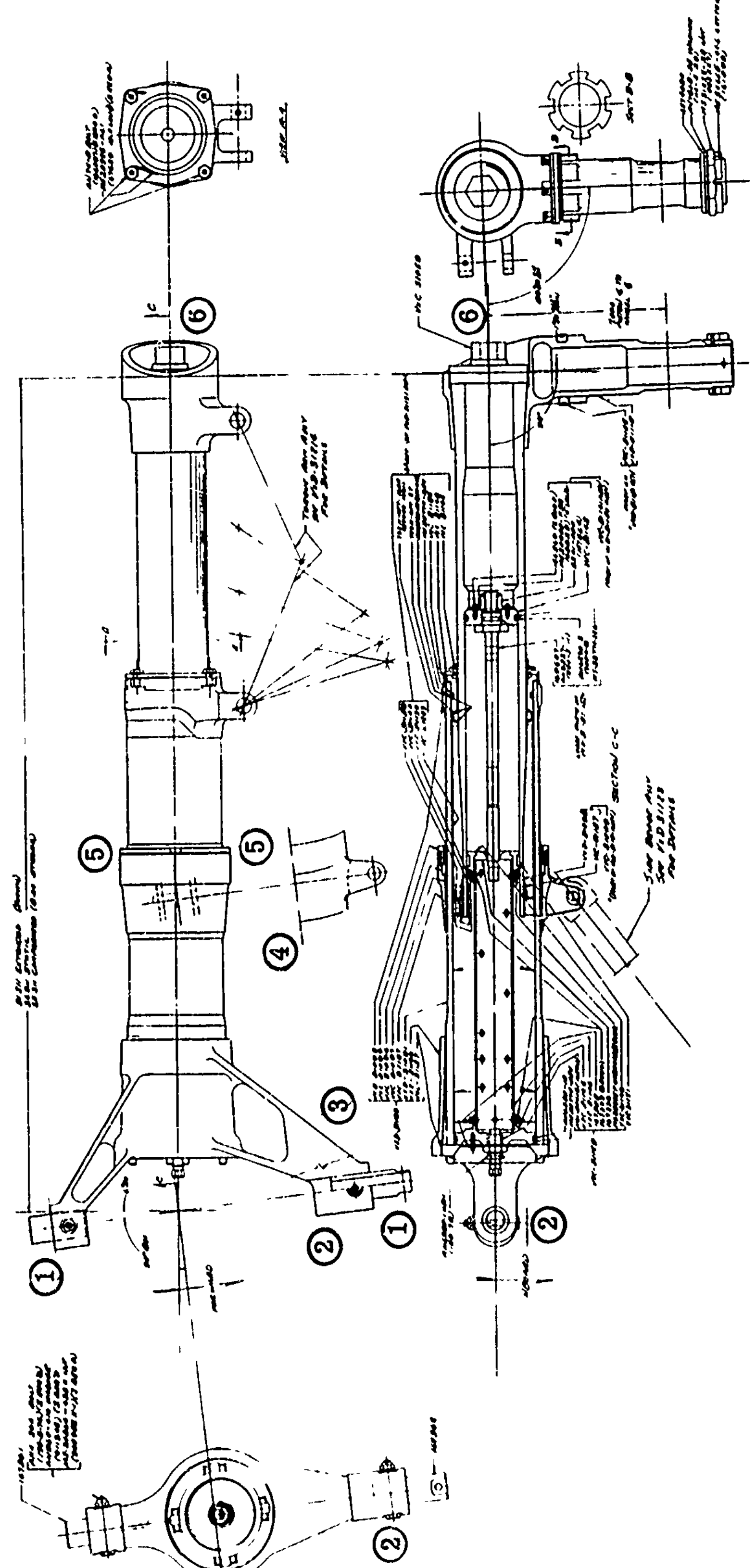


Figure 6-9. Shock Absorber Assembly, Test Version

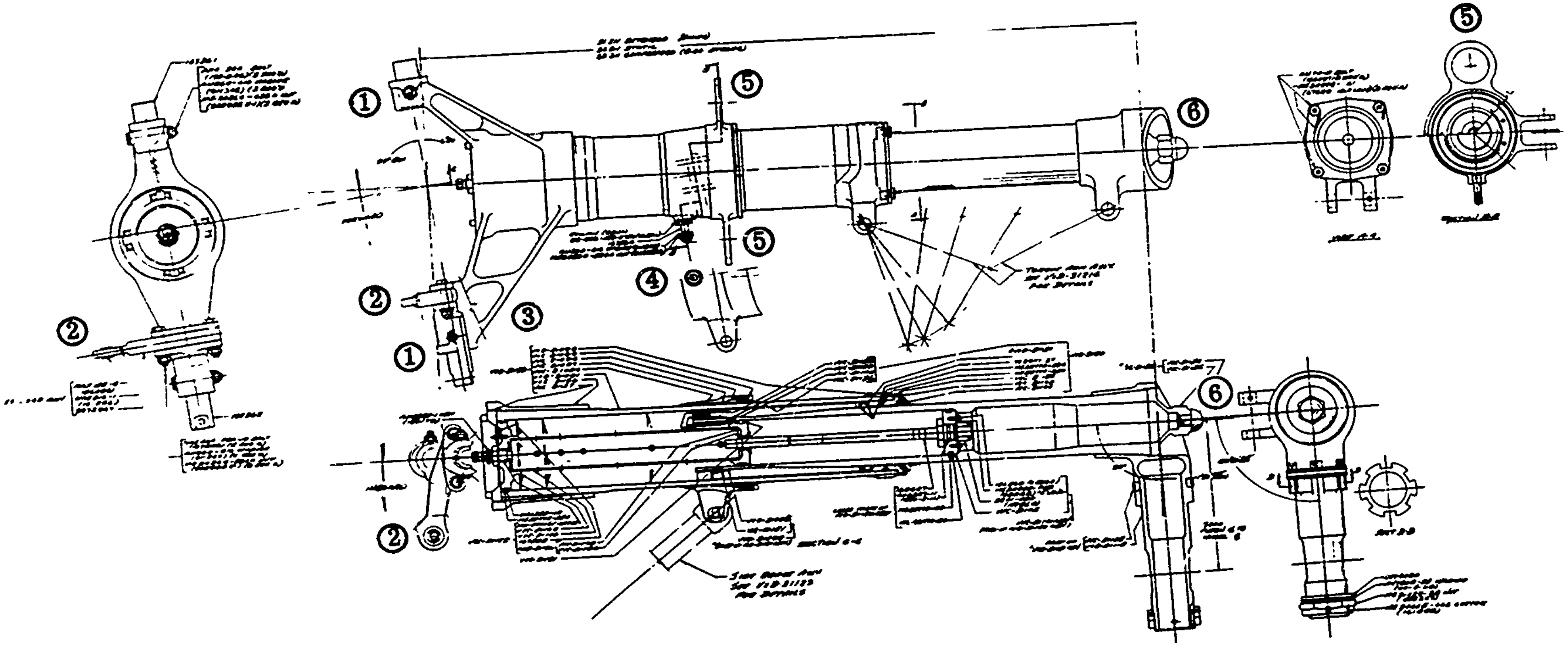



Figure 6-10. Boron-Epoxy Shock Absorber Assembly Aircraft Version

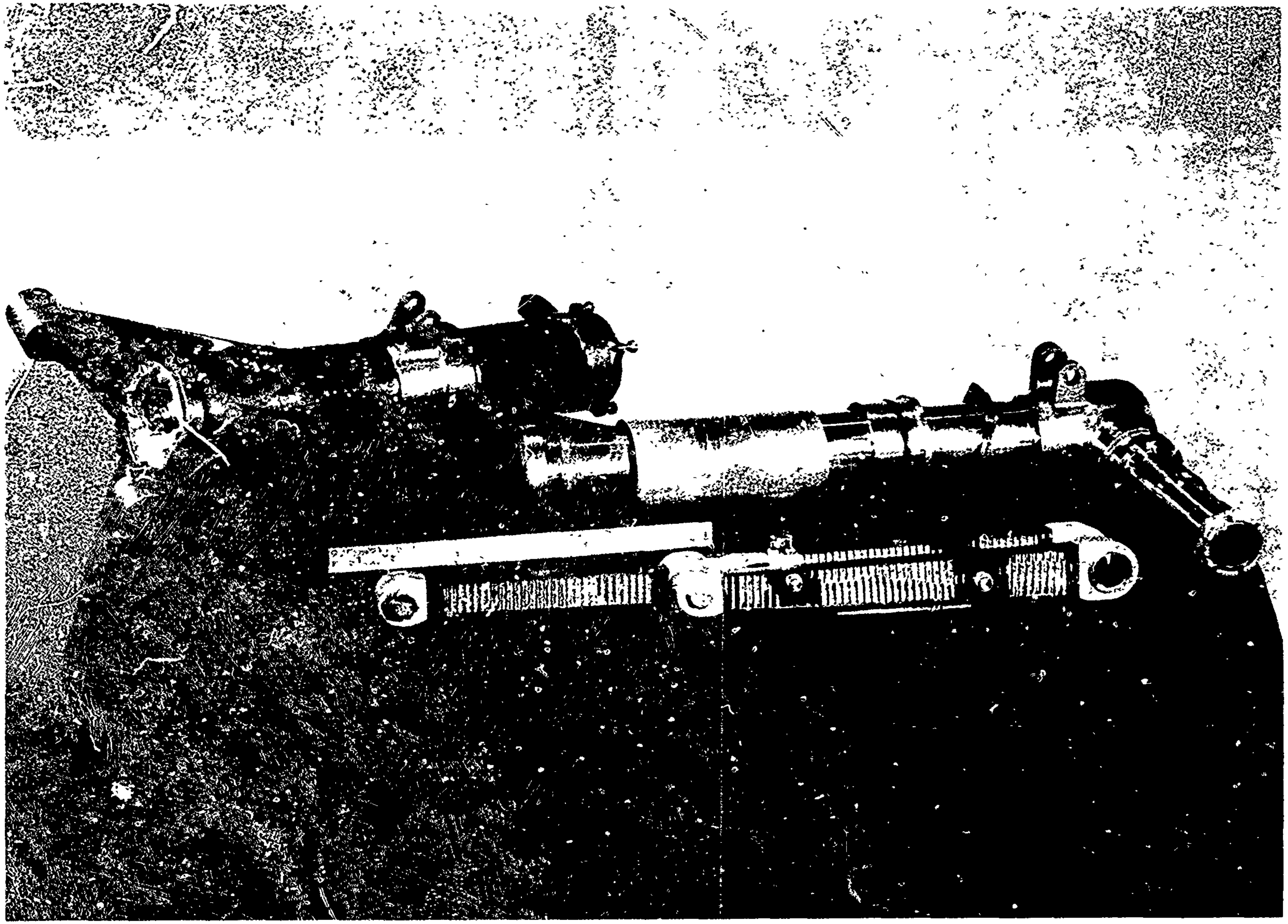


Figure 6-11. Completed Composite Landing Gear Components (P-25150T)

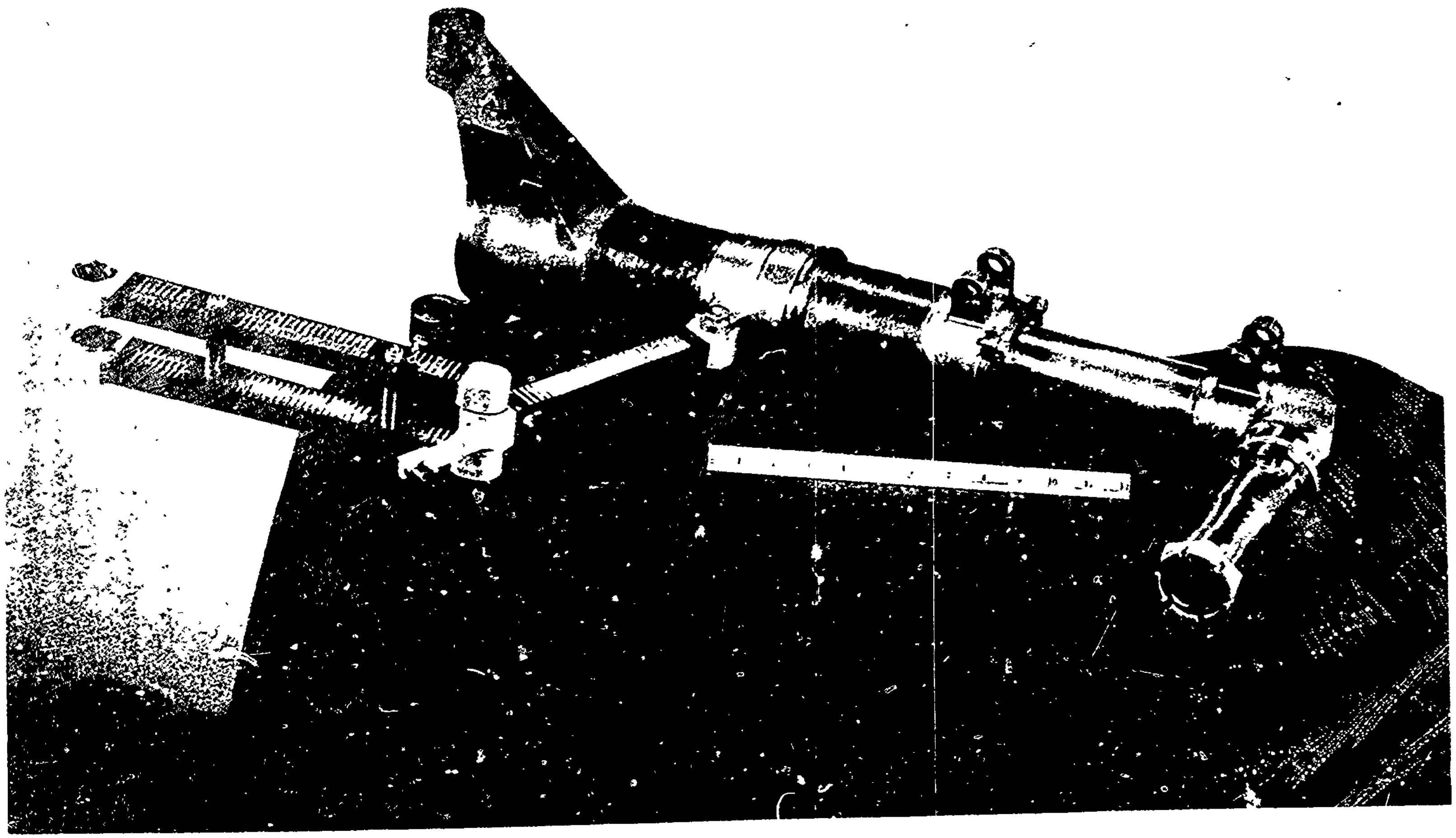


Figure 6-12. Completed Composite Landing Gear Assembly (P-25150U)

## SECTION VII

## LANDING GEAR TESTING

### 7.0 INTRODUCTION

This section details the results of the leakage tests performed on the shock absorber assembly and of the ground loads structural tests applied to the shock absorber and side brace assemblies. The discussion ends with a performance review which results in recommendations for the improvement of the design and construction of filament composite landing gear.

### 7.1 LEAKAGE TESTS

Purpose - To check for sealing defects.

Information Required - Location and amount of leakage if any.

#### 7.1.1 Extended Leakage Test

Procedure - MIL-L-8552C, Paragraph 4.6.2.5.

1. Install landing gear assembly in vertical position in loading rig, Figure 7-1.

2. Fill with required volumes of hydraulic fluid and "air." Use MIL-H-6083C oil and pressurize with dry nitrogen.

3. Block piston in 1.0 in. compressed position. Inflate to 90 psig extended air pressure. Spray piston with coat of dye check developer (white powder) to check lower seal leakage. Hold in this position for six hours. Record location and amount of any leakage. Periodically record air pressure.

4. Release piston to fully extended position (no external support on piston). Inflate to 90 psig air pressure. Spray piston with coat of dye check. Gear assembly to remain in this position for two hours. Record location and amount of any leakage. Periodically record air pressure.

5. If any leakage has occurred, reinflate to 90 psig. Cycle the piston six times over a distance of 3.0 inches from fully extended. Record amount and location of any leakage.

Results - There was no perceptible leakage or loss of pressure incurred during this test.

7.1.2 Vertical Position Leakage Test

Procedure - MIL-L-8552C, Paragraph 4.6.2.7

1. Install landing gear assembly in vertical position in loading rig, Figure 7-2.

2. Block in static position, 6.4 inches compressed, and inflate to 410 psig (static air pressure). Spray all composite parts with dye check developer as a leakage detector. Hold in this position for 24 hours.

3. Record air pressure periodically. Record location and amount of any leakage.

Results - There was no perceptible leakage or loss of pressure incurred during this test.

7.1.3 Horizontal Position Leakage Test

Procedure - MIL-L-8552C, Paragraph 4.6.2.6

1. Support the shock absorber horizontally with the piston in the fully extended position, Figure 7-3. Inflate to the extended air pressure of 90 psig. Spray piston with dye check developer. Hold in this position for eight hours.

2. Record air pressure periodically. Record location and amount of any leakage.

Results - No perceptible leakage or loss of pressure occurred during this test.

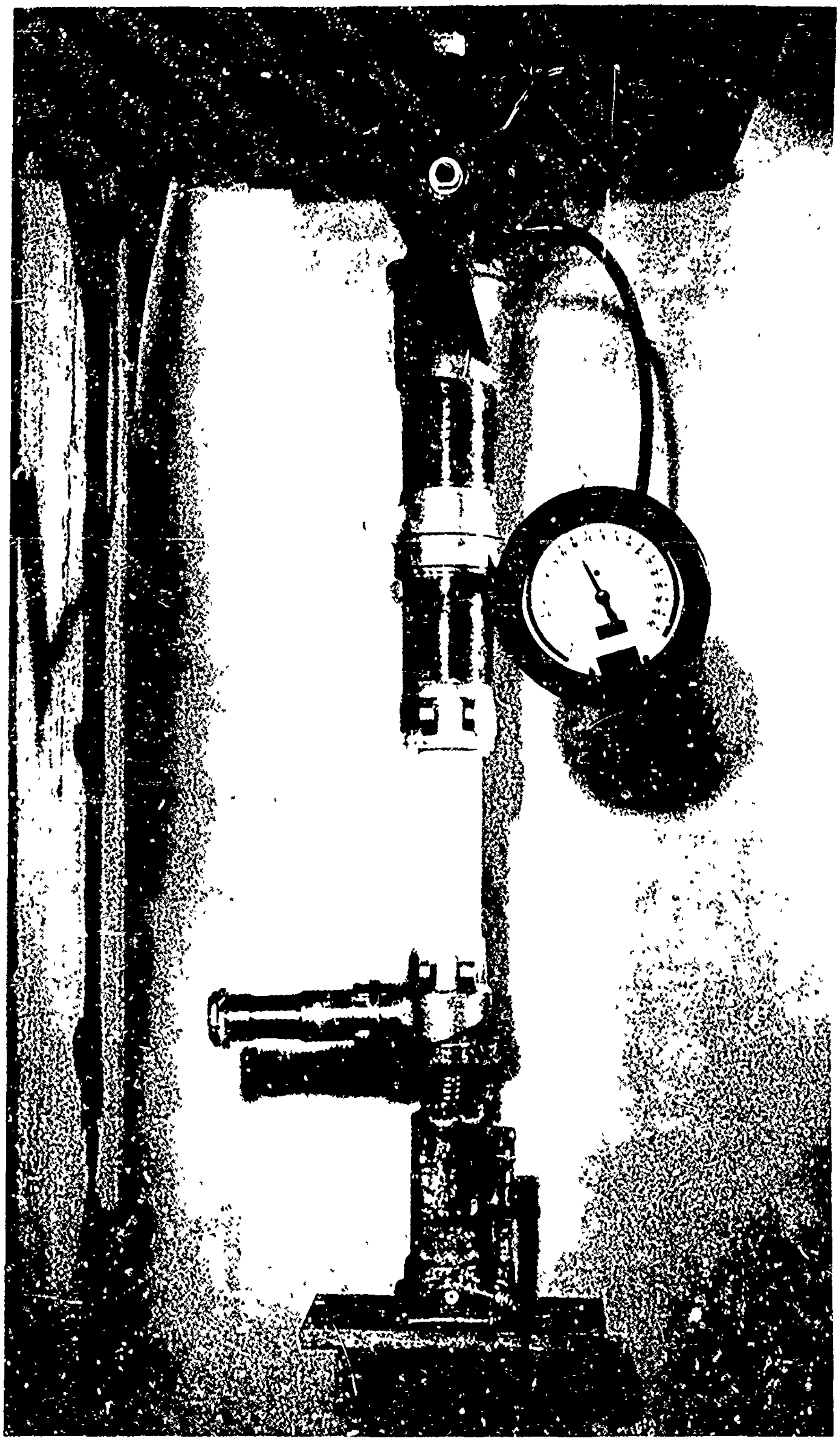


Figure 7-1. Setup for Extended Leakage Test (P-25150AA)

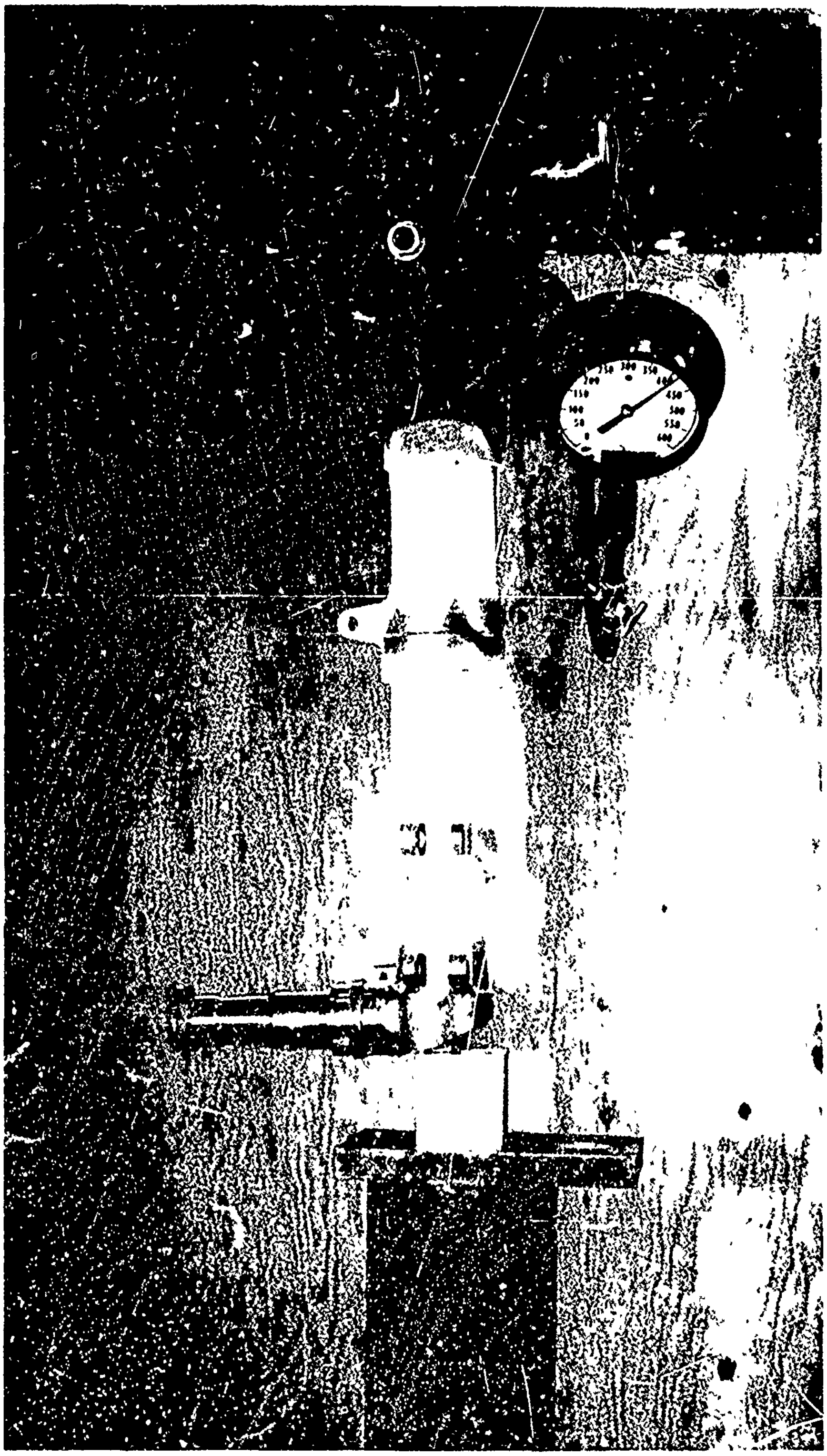


Figure 7-2. Setup for Vertical Position Leakage Test (P-25150Y)

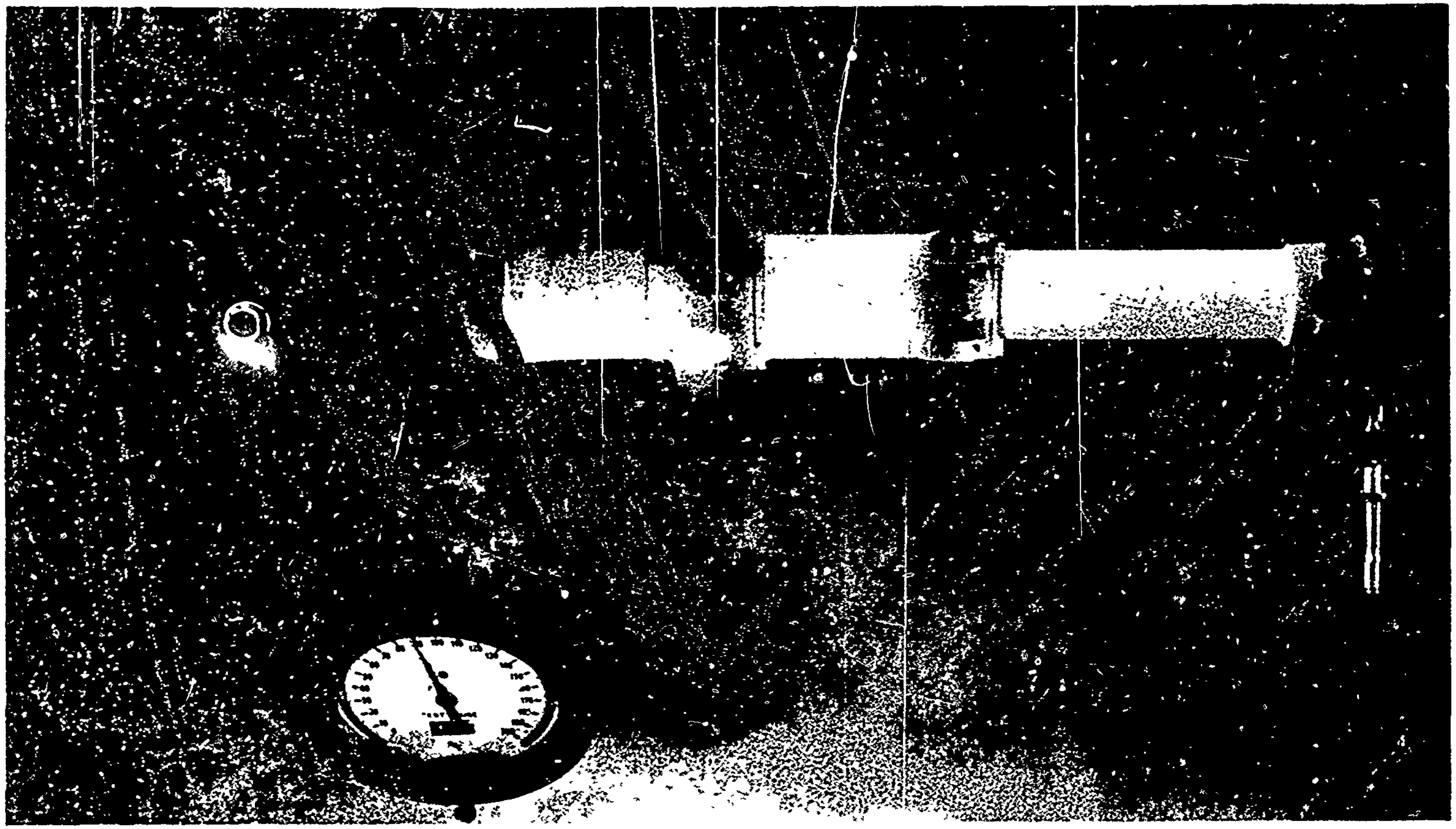


Figure 7-3. Setup for Horizontal Position Leakage Test (P-25150X)

## 7.2 STRUCTURAL TESTS

The following discussion deals with the proof pressure testing of the piston high pressure chamber and the ground loads structural testing of the shock absorber and side brace assemblies.

### 7.2.1 Piston Proof Pressure Test

Purpose - To determine structural integrity of piston dynamic pressure chamber.

Information Required

1. Strain gage readings.

2. Location, extent, and nature of any leakage or structural damage.

Procedure - MIL-L-8552C, Paragraph 4.6.2.2

1. Disassemble piston assembly, Figure 7-4, from shock absorber assembly.

2. Apply strain gages at locations shown in Figure 7-4. Use gages suitable for use on the thick nickel liner. Wire gages to X-Y plotting board.

3. Insert pressure plug to position shown in Figure 7-4. Block pressure plug and lower end of piston between external supports.

4. Measure OD of cylinder.

5. Pressurize cavity in three steps.

   (a) Load to 1500 psi and release.

   (b) Load to 2100 psi and release.

   (c) Load to 2650 psi and hold for 15 minutes. Loading and unloading rate to be 100 psi per second. (2650 psi corresponds to limit load, 2 point level landing, maximum vertical reaction, Table 4-1).

6. For each loading record strains.

7. After each loading measure cylinder OD and examine piston for signs of yield, leakage, or permanent deformation. Do not dismantle assembly until after last loading. Record any leakage or damage.

Results - There were no signs of yielding, leakage, or permanent deformation after any of the three tests. The OD of the piston measured 2.676 inches before testing and there was no change after completion of testing.

Only one of the two strain gages functioned properly during the test. The results from this gage are shown in Figure 7-7. The plot is shown for the highest loading only. The curves for the lower loads coincided in slope and reversal with the curve shown.

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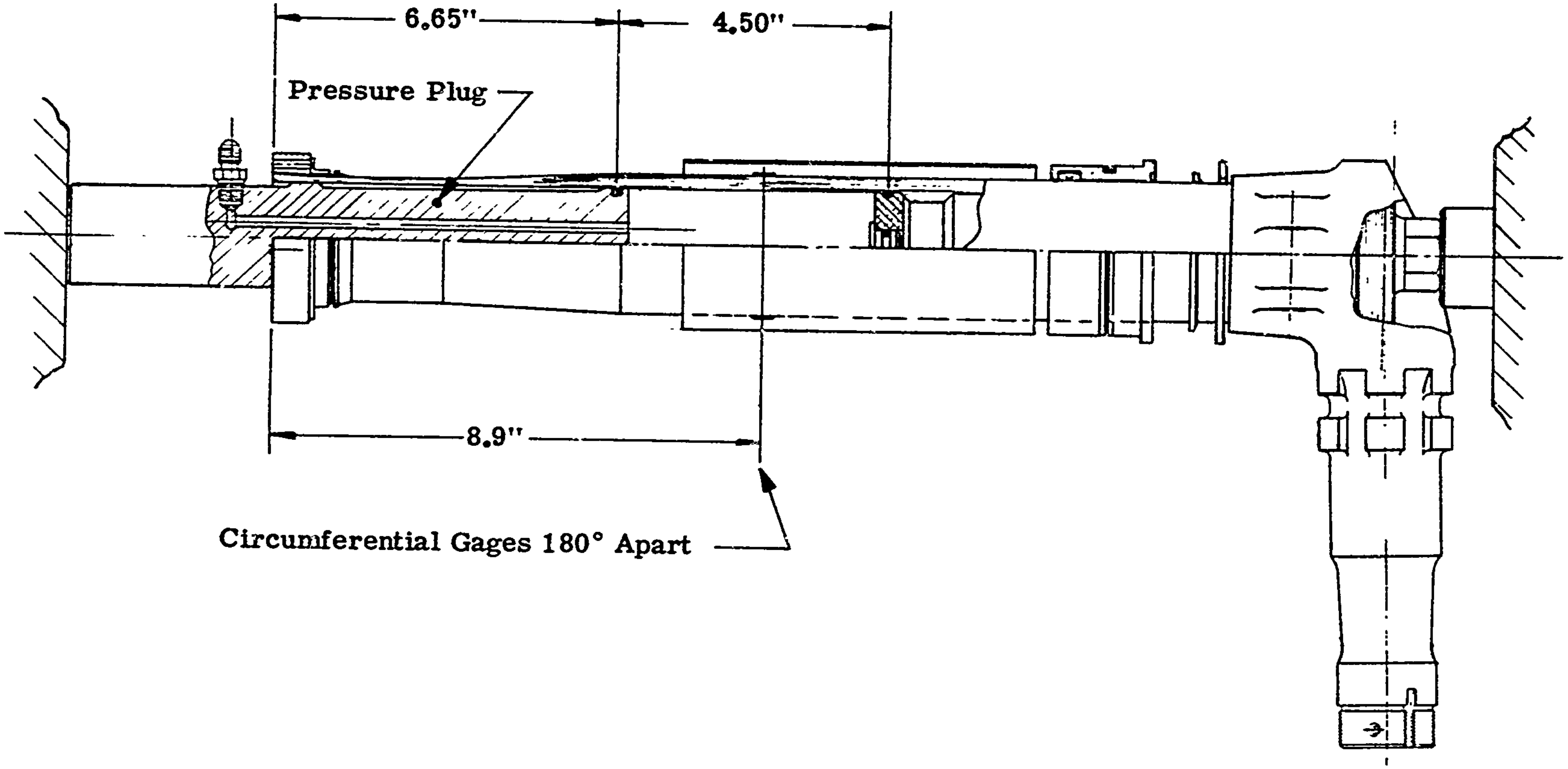



Figure 7-4. Proof Pressure Test

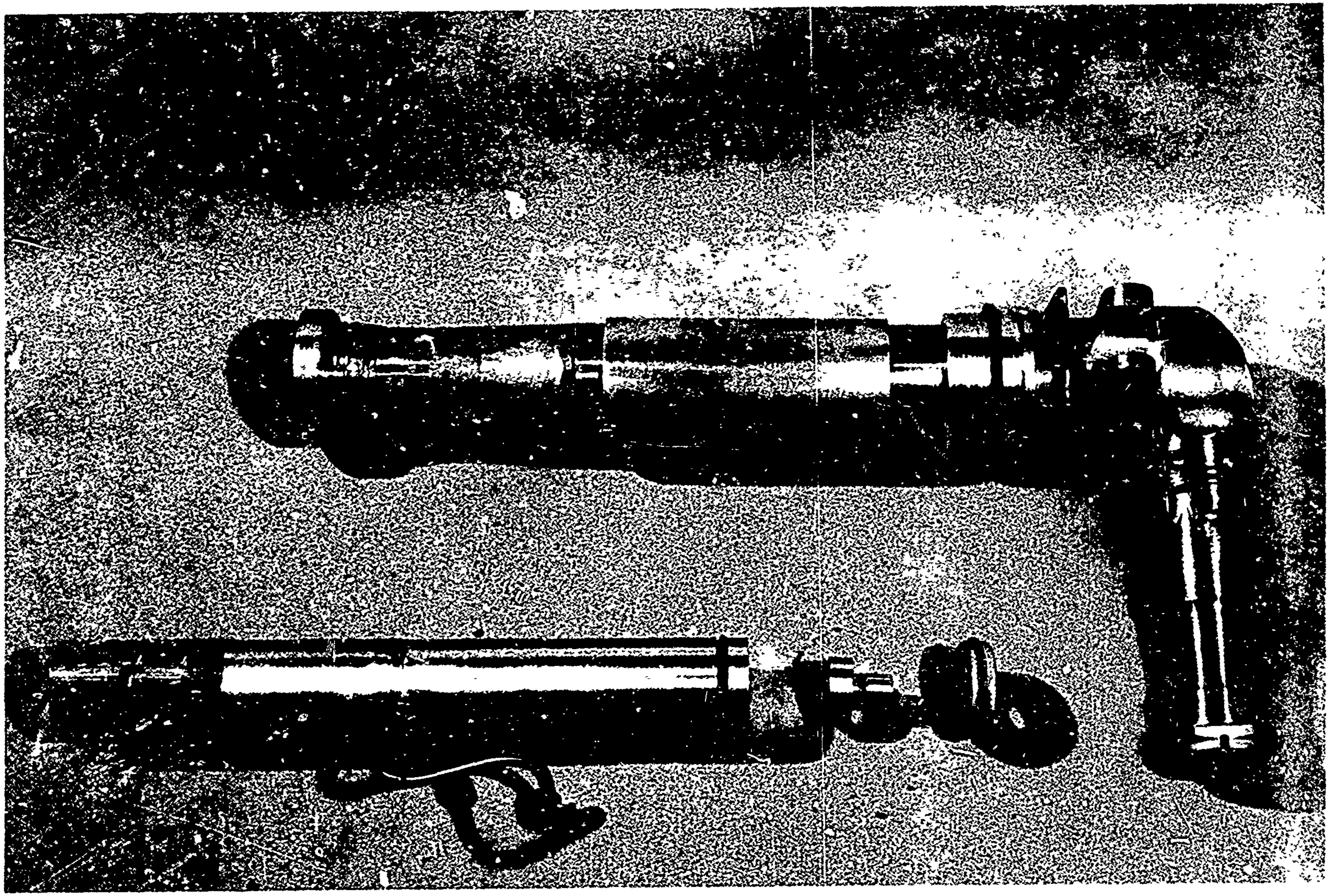


Figure 7-5. Proof Pressure Test Hardware (P-25150CC)

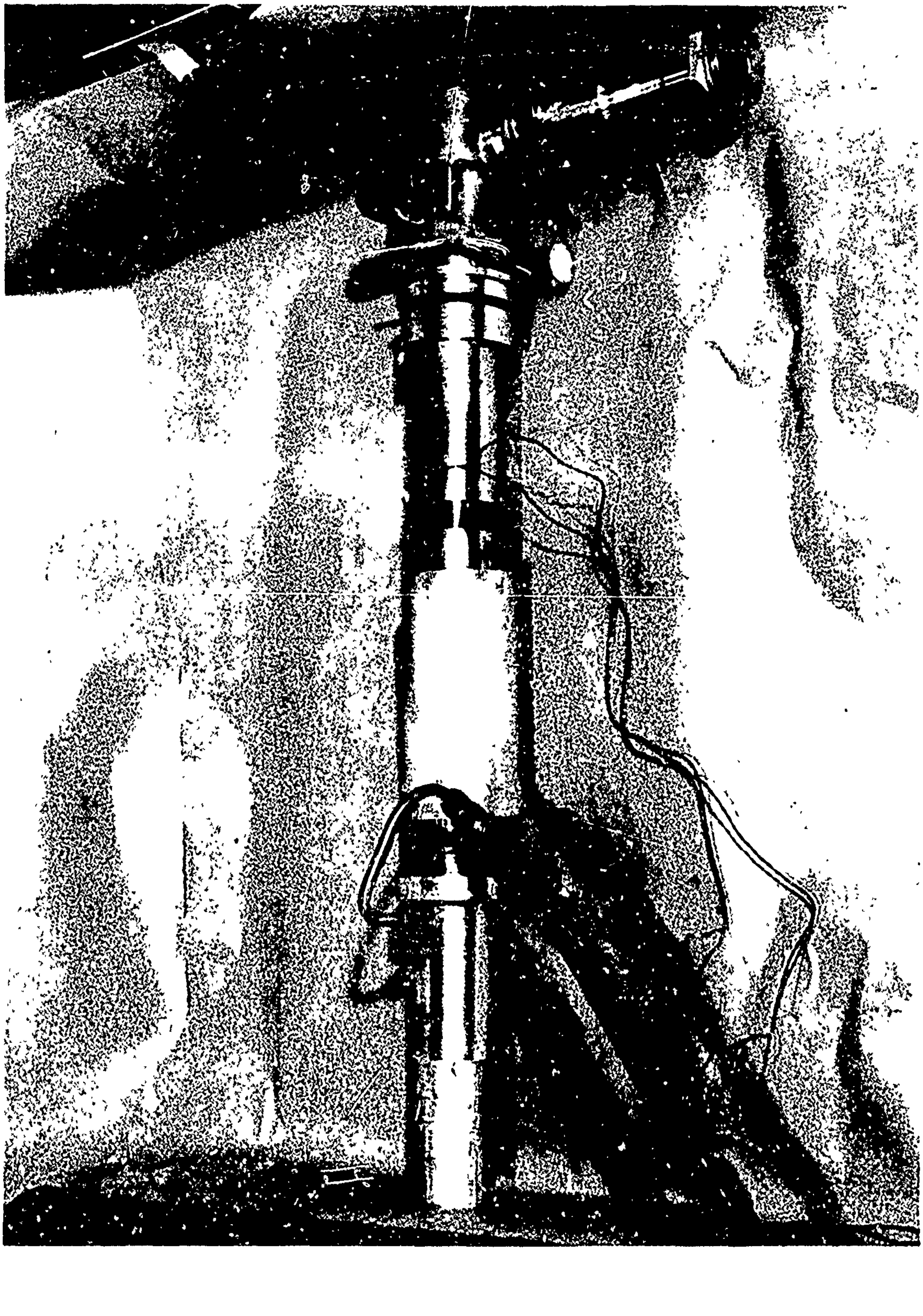


Figure 7-6. Proof Pressure Test Setup (P-25150BB)

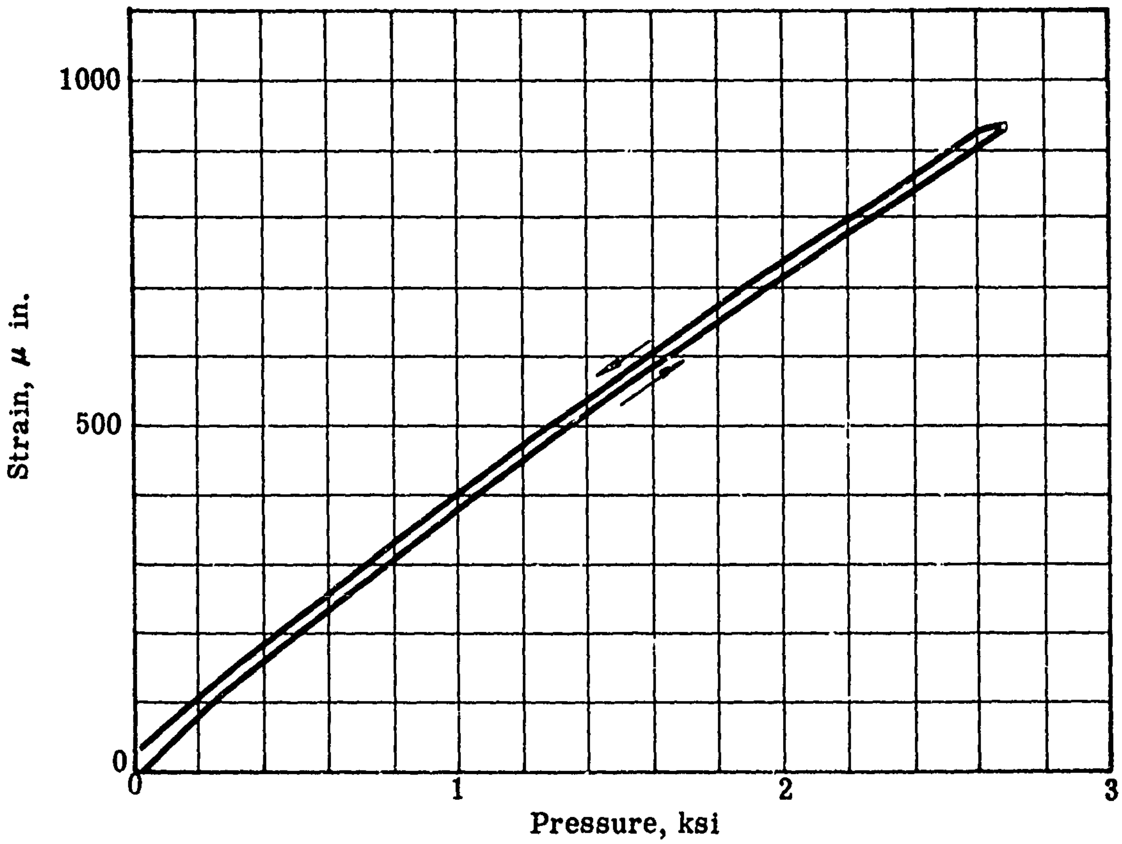



Figure 7-7. Strain Gage Response Piston Proof Pressure Test

### 7.2.2 Ground Loads Testing

Structural testing was performed to determine the ability of the filament composite gear assembly to support the critical design ultimate ground loads given in Tables 4-1 and 4-2. The gear was tested as two separate components, the shock absorber in one test and the side brace in a second test, rather than as an assembly. This procedure was employed in order to avoid unintentional damage to one component as a result of a possible premature failure in the other.

#### 7.2.2.1 Shock Absorber Test

1 Test Setup

The shock absorber assembly was installed in a loading fixture incorporating a support geometry identical to that in the aircraft, Figures 7-8 and 7-9. Ground loads were applied through an axle fixture simulating the wheel and brake action, Figures 7-10 and 7-11. The loads were applied by hydraulic jack along lines passing through the theoretical ground contact point. The load direction coincided with the load resultant of the $X_A$, $Y_A$ and $Z_A$ components from Table 4-1.

The load geometry was related to the three design critical loading conditions as indicated below in Table 7-1.

TABLE 7-1. LOADING DEFINITION

| | Table 4-1 Condition | Test Condition | Piston Compressed |
|---|---|---|---|
| Drift Landing - Right | 2A | $P_{dr}$ | 4 in. |
| Drift Landing - Left | 2C | $P_{dl}$ | 4 in. |
| Reverse Brake | 5A | $P_{rb}$ | 6.4 in. |

A photograph of the landing gear assembly in the test set-up is shown in Figure 7-12. This illustrates the complete assembly combining the three filament composite components - the side brace, outer cylinder and piston. Loading jacks are shown in place for both the $P_{dr}$ and $P_{dl}$ test conditions although in actual test, one jack is applied at a time.

2 Loading

Loading and structural performance are summarized in Table 7-2. Comments pertaining to the various column headings are given below.

Load Sequence - Load magnitudes and directions were applied in order of increasing severity (less severe first) as indicated by the load conditions of Table 7-1 and as revealed by structural problems occurring during the course of the tests.

Load Condition - Referring to Table 7-1,

$dr = P_{dr}$, drift right

$dl = P_{dl}$, drift left

$rb = P_{rb}$, reverse brake

Load, Load Range - Loads were applied in three groups aimed at achieving the following load levels:

50% design limit - loadings 1 to 6
100% design limit - loadings 7 to 19
150% design limit - loadings 20 to 31

Percent Limit - 100 percent design limit magnitude for each of the load conditions is as follows:

dr = 6100 lbs.
dl = 6600 lbs.
rb = 9000 lbs.

Pressure - This is the internal fluid pressure reacting the ground load component acting parallel to the piston center line. This is the maximum value measured during each loading. The internal pressure load does not equal the externally applied load since part of the applied load was resisted by friction at the main bearings.

Piston Block - An internal piston block was required to hold the piston in the proper stroke position, reference Table 7-1. As long as the shock absorber was capable of supporting internal pressure, the piston stroke was maintained by filling the assembly completely with hydraulic fluid, then adjusting the stroke by adding or removing fluid through the filler plug at the top of the outer cylinder. In case of fluid pressure loss, an internal metallic spacer was employed, Figure 7-13.

Side Brace - In order to avoid unintentional damage to the filament composite side brace as a result of premature failure in the shock absorber, it was decided to test the side brace in a separate component test, Paragraph 7.2.2.2. In order to provide side support for testing the shock absorber, three different metal side braces were used. For loads up to limit magnitude the regular side brace currently on the A37-B aircraft was used, Figure 7-14. For dl (drift left) loads, which impose compression on the brace, a solid aluminum bar was used to eliminate the possibility of column buckling of the brace at the higher load levels, Figure 7-17. After failure of the bond between the side brace fitting and the outer cylinder, it was no longer possible to support vertical load components at the side brace attachment and a horizontal reacting brace was used for dl loadings, Figure 7-21.

Piston - After rupture of the composite piston, a steel simulated piston was used for continued loading of the outer cylinder, Figure 7-24.

## 3 Review of Test Results

Stresscoat Survey and Strain Gage Application - Before loading, the shock absorber was covered (sprayed) with ST-101 Aerosol Stresscoat lacquer. The purpose of the stresscoat covering was to assist in determining regions of highest strain for later application of strain gages. The stresscoat survey was accomplished during loading, sequence 1 thru 6, Table 7-2. The shock absorber assembly after the stresscoat survey is shown in Figure 7-14.

Strain gages were applied prior to application of Load 7, Table 7-2. Strain gage locations were determined on the basis of stresscoat patterns which indicate regions of maximum "tensile" strains and by analysis for regions of "compressive" strains. Gages were wired to a BLH Electronics Mc., Model 160 Strain Gage Scanner. The primary purpose of the gages was to monitor strains during progress of the test to assist in predicting problem areas during subsequent higher loadings. For the results of the strain gage analysis, see Appendix E-3.

Load No. 5, Disassembly of Side Brace Fitting - After application of this load, inspection of the shock absorber revealed considerable flaking of the stress coat lacquer on the urethane fillet along the upper edge of the cylindrical sleeve which joins the side brace to the outer cylinder. (This joint assembly is illustrated in Figures 5-80 and 5-81 and the associated discussion.) The condition of the joint indicated some possible downward movement of the metal sleeve with respect to the composite outer cylinder. It was decided to disassemble the joint and to reassemble it by application of cement to all contact surfaces. It was thought that the adhesive would provide more positive retention than a purely mechanical joint. This operation was performed in the following steps.

1. Disassembled joint without removing parts from the outer cylinder.
2. Removed urethane from all surfaces.
3. Cleaned glass overwrap and all metal surfaces with 400 SiC grit paper.
4. Wiped all surfaces with MEK solvent.
5. All surfaces were coated with Epon 934 room temperature set resin.
6. The joint was reassembled and the spanner nut pulled up tight.

(The original assembly of the side brace fitting is described in Paragraph 8.2.5.2, Bendix Activities.)

The loading was changed to the rb condition which is less critical for loading on the side brace fitting, reference Table 7-2.

Load No. 8, Bond Failure - Torque Arm Fitting - Failure of the bond between the torque arm fitting and the outer cylinder was incurred during application of the rb loading, Table 7-1 and Figure 7-16. This is the loading condition which produces the highest torque arm loading and torsion about the shock absorber center line.

The shock absorber was disassembled, the torque arm fitting removed, the mating surfaces cleaned, and the joint reassembled using Epon 934 room temperature curing cement. The joint was cured for eight days prior to reloading.

The loading was changed to the dl condition which is less critical for loading on the torque arm fitting, Table 7-2.

Load No. 17, Oil Leakage - Some leakage of oil across the lower bearing seal was detected during application of this load. This leakage was overcome during subsequent loadings by increasing the shock absorber internal fluid pressure with a hand pump.

Load 19, Crack in Outer Cylinder Wall - Immediately after reading 100 percent limit level for the rb loading, a cracking sound was heard and oil was observed leaking from the outer cylinder at the lower edge of the trunnion socket. The shock absorber was disassembled and examined. A longitudinal crack on the outer surface of the outer cylinder, Figure 7-18, and wrinkling of the nickel liner, Figure 7-19, were evident.

Since the shock absorber was no longer capable of supporting internal pressure, a steel spacer was installed to support the piston in the correct stroke position, Figure 7-13. The loading condition was changed to the dr direction which is less critical for outer cylinder bending, Table 7-2.

Load 25, Bond Failure - Glass Overwrap - Upon reaching 88 percent of limit load for the dl condition, a bond failure was sustained at the side brace fitting, Figure 7-20. The failure was along the interface between the glass overwrap and the boron composite cylinder. It may be noted that this joint successfully supported 100 percent limit load on a previous occasion (see Load 11).

In order to continue loading in the dl direction, a horizontal brace was installed to eliminate the vertical load component on the side brace fitting, Figure 7-21.

Load 26, Run in Piston OD Nickel Plate - The nickel liner on the piston outer surface contained a crack flaw from the moment of manufacture, Figure 8-103. Upon application of this load, the crack ran longitudinally along the cylinder over the distance from the lower end of the outer cylinder to the axle socket.

Load 28, Rupture of Piston Cylinder - A rupture of the piston cylinder was experienced at 112 percent of limit level for the dl loading, Figures 7-22 and 7-23. The rupture occurred at the piston section subjected to the maximum bending moment which coincides with the lower main bearing.

Load 31, Rupture of Outer Cylinder - After destruction of the piston, the outer cylinder was still intact. It was desired to determine the strength of the outer cylinder for the critical design loading rb. In order to load the outer cylinder in the test setup (already available from previous testing), a simulated piston was manufactured from steel bar stock, Figure 7-24, and assembled into the outer cylinder. In the loading setup, Figure 7-25, the more flexible conventional side brace was employed in order to minimize support of the outer cylinder in the load direction.

Upon loading rb to 120 percent of design limit load, two failures occurred. One was rupture of the outer cylinder tube at its point of entry into the trunnion socket, Figures 7-25 and 7-26. Also evident was the failure of the bond between the torque arm fitting and the composite cylinder, Figure 7-27. There was no indication as to which failure occurred first or whether the occurrence of one precipitated the other.

## TABLE 7-2. GROUND LOAD SUMMARY, SHOCK ABSORBER

| Load Sequence | Load Condition | Load, lbs. | % Limit | Pressure psig | Load Range | Piston Block | Side Brace | Piston | Comments | Figure Number |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | dr | 1500 | 25 | | | | | | | |
| 2 | dr | 3000 | 50 | | Up to | | | | | |
| 3 | dl | 1650 | 25 | 305 | 50% | | | | | |
| 4 | rb | 2250 | 25 | 50 | limit | | | | | |
| 5 | dl | 3300 | 50 | 85 | | | | | Side brace sleeve slipped | |
| 6 | rb | 4500 | 50 | | | | Regular | | | |
| 7 | rb | 2210 | 24.5 | | | | | | | |
| 8 | rb | 4500 | 50 | | | | | | Failed bond at torque arm fitting. | 7-16 |
| 9 | dl | 3300 | 50 | | | | | | | |
| 10 | dl | 5000 | 76 | 100 | | Fluid | | | | |
| 11 | dl | 6600 | 100 | | | | | | | |
| 12 | dr | 1460 | 24 | 130 | | | | | | |
| 13 | dr | 3020 | 49.5 | 320 | Up to | | | | | |
| 14 | dr | 4575 | 75 | 490 | 100% | | Simulated | | | |
| 15 | dr | 6100 | 100 | 680 | limit | | | | | |
| 16 | rb | 2280 | 25 | 50 | | | | Composite | | |
| 17 | rb | 4500 | 50 | 60 | | | | | Oil leak around lower seal. | |
| 18 | rb | 6750 | 75 | 90 | | | | | | |
| 19 | rb | 9000 | 100 | 150 | | | | | Crack in outer cylinder wall. | 7-18, 7-19 |
| 20 | dr | 6350 | 104 | | | | | | | |
| 21 | dr | 7700 | 126 | | | | Regular | | | |
| 22 | dr | 8550 | 140 | | Up to | | | | | |
| 23 | dr | 9300 | 152 | | 150% | | | | | |
| 24 | dr | 6100 | 100 | | limit | | | | | |
| 25 | dl | 5800 | 88 | | | Spacer | | | Sheared glass bond at side brace fitting. | 7-20 |
| 26 | dl | 6300 | 100 | | | | | | Nickel crack on piston ran. | |
| 27 | dl | 3300 | 50 | | | | Horizontal | | | |
| 28 | dl | 7400 | 112 | | | | | | Ruptured piston | 7-22, 7-23 |
| 29 | rb | 4350 | 49 | | | | | | | |
| 30 | rb | 8880 | 99 | | | | Regular | Steel | | |
| 31 | rb | 10800 | 120 | | | | | | Ruptured outer cylinder. Failed bond at torque arm fitting. | 7-25, 7-26, 7-27, 7-28 |

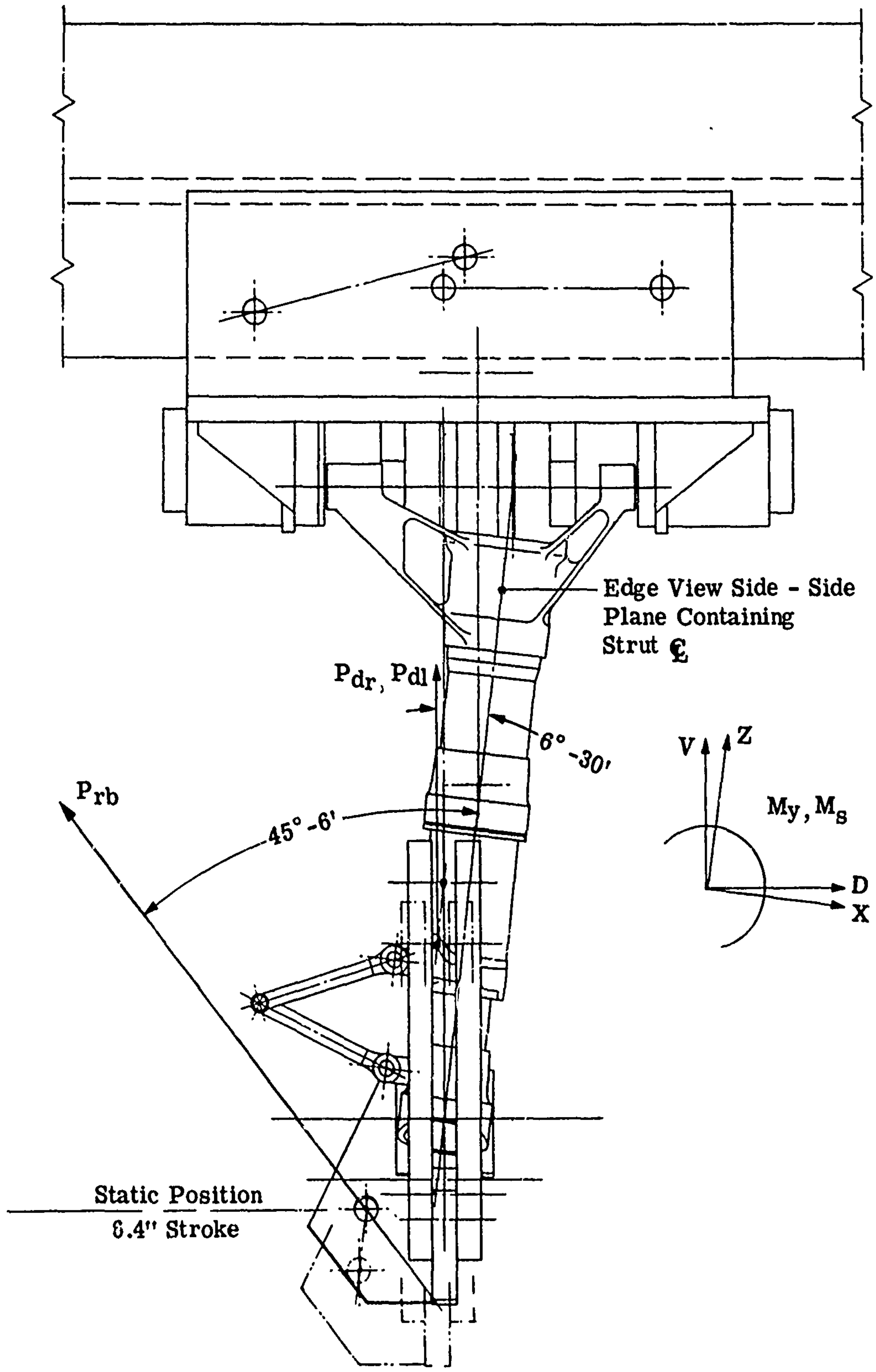



Figure 7-8. Gear Assembly in Static Loading Rig

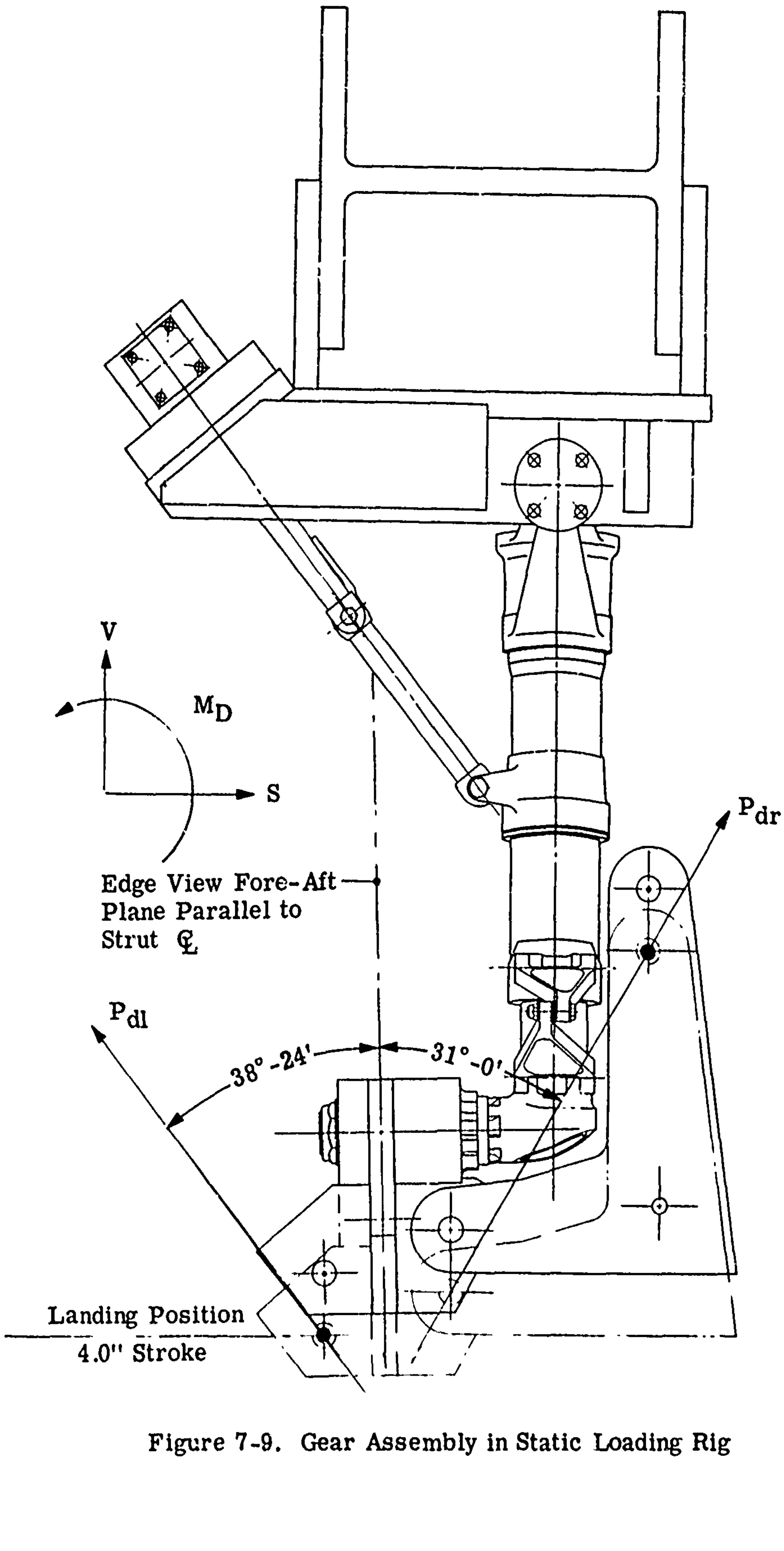



Figure 7-9. Gear Assembly in Static Loading Rig

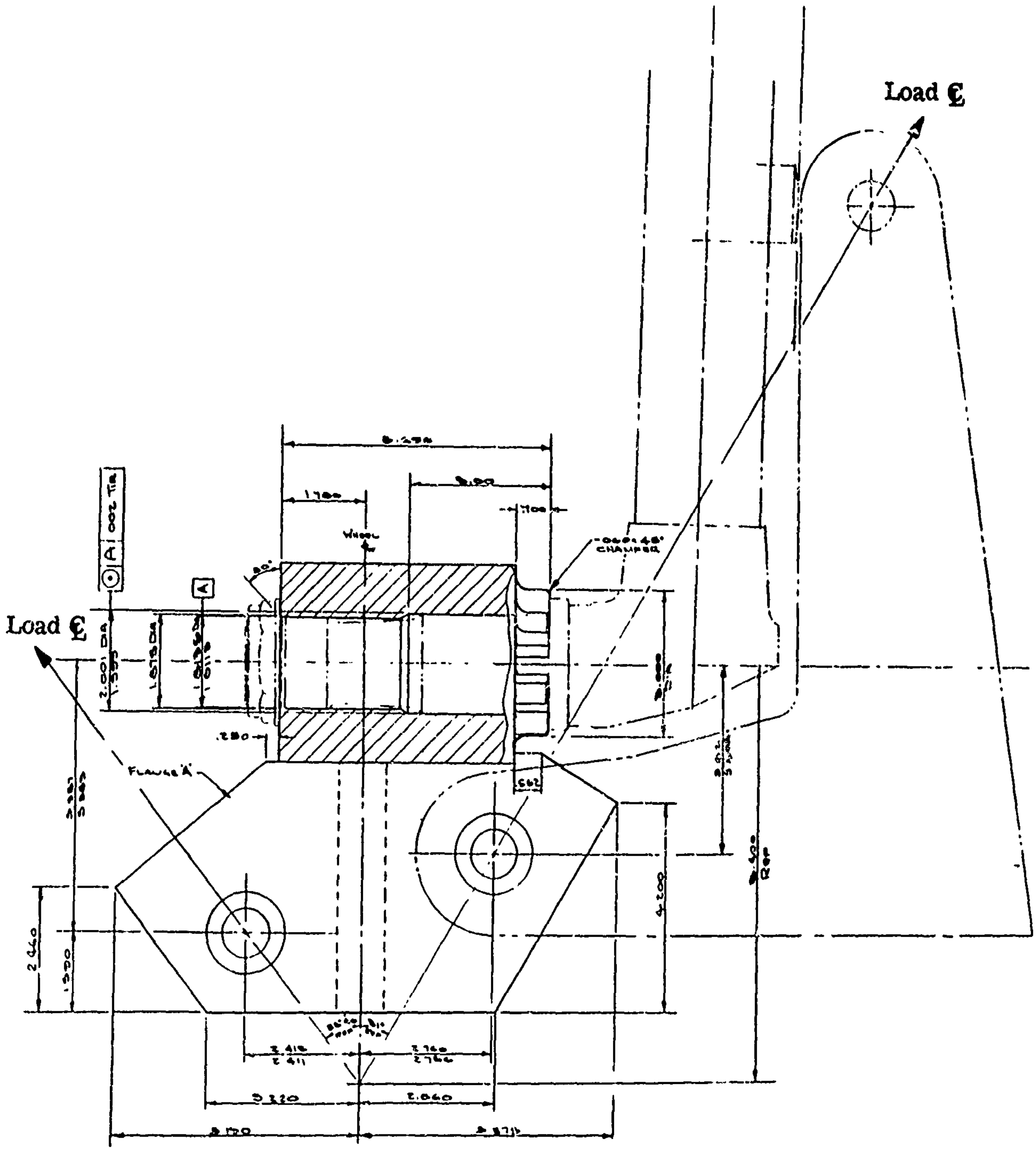



Figure 7-10. Static Load Fixture, Wheel Simulator, Looking Aft

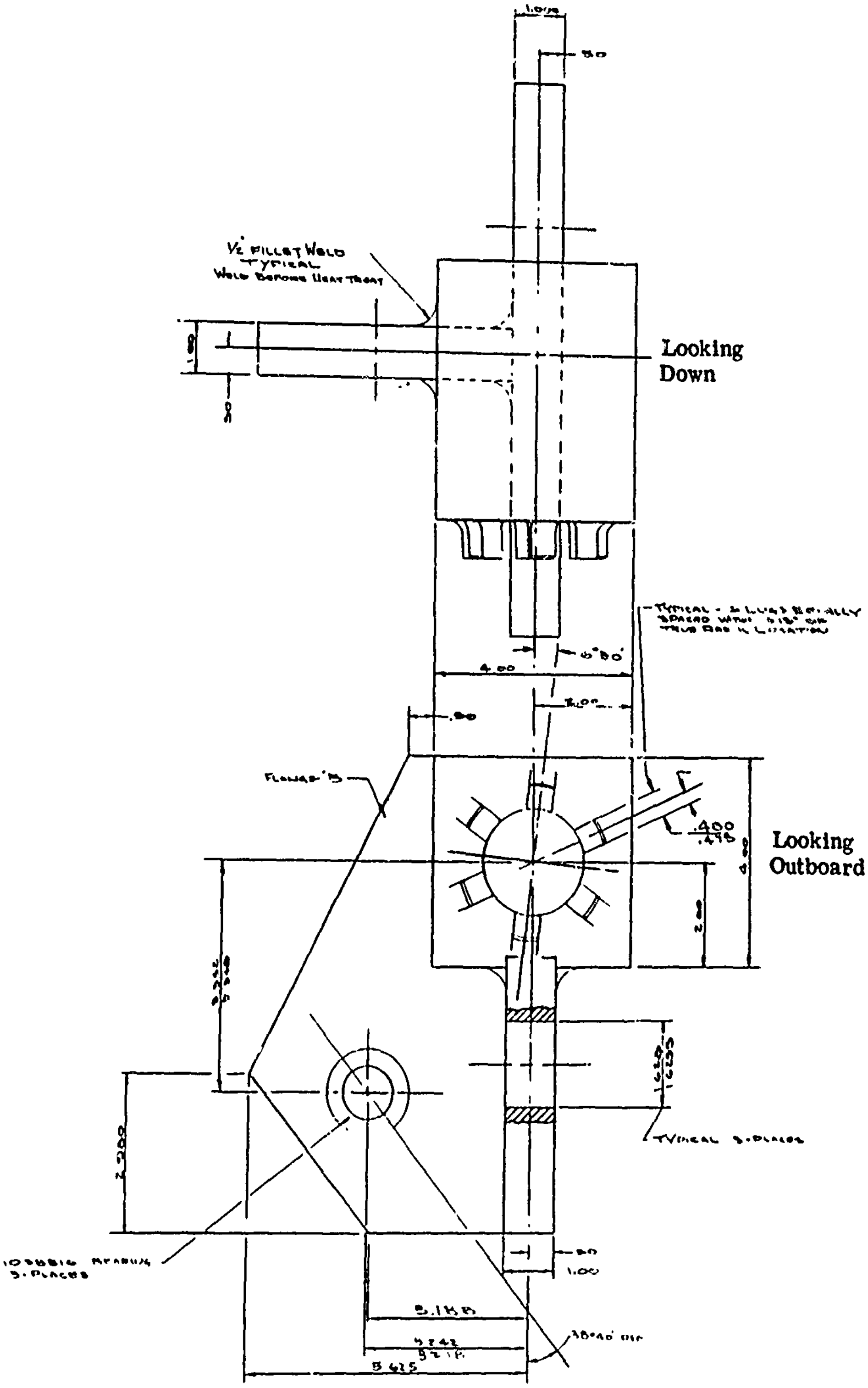



Figure 7-11. Static Load Fixture, Wheel Simulator

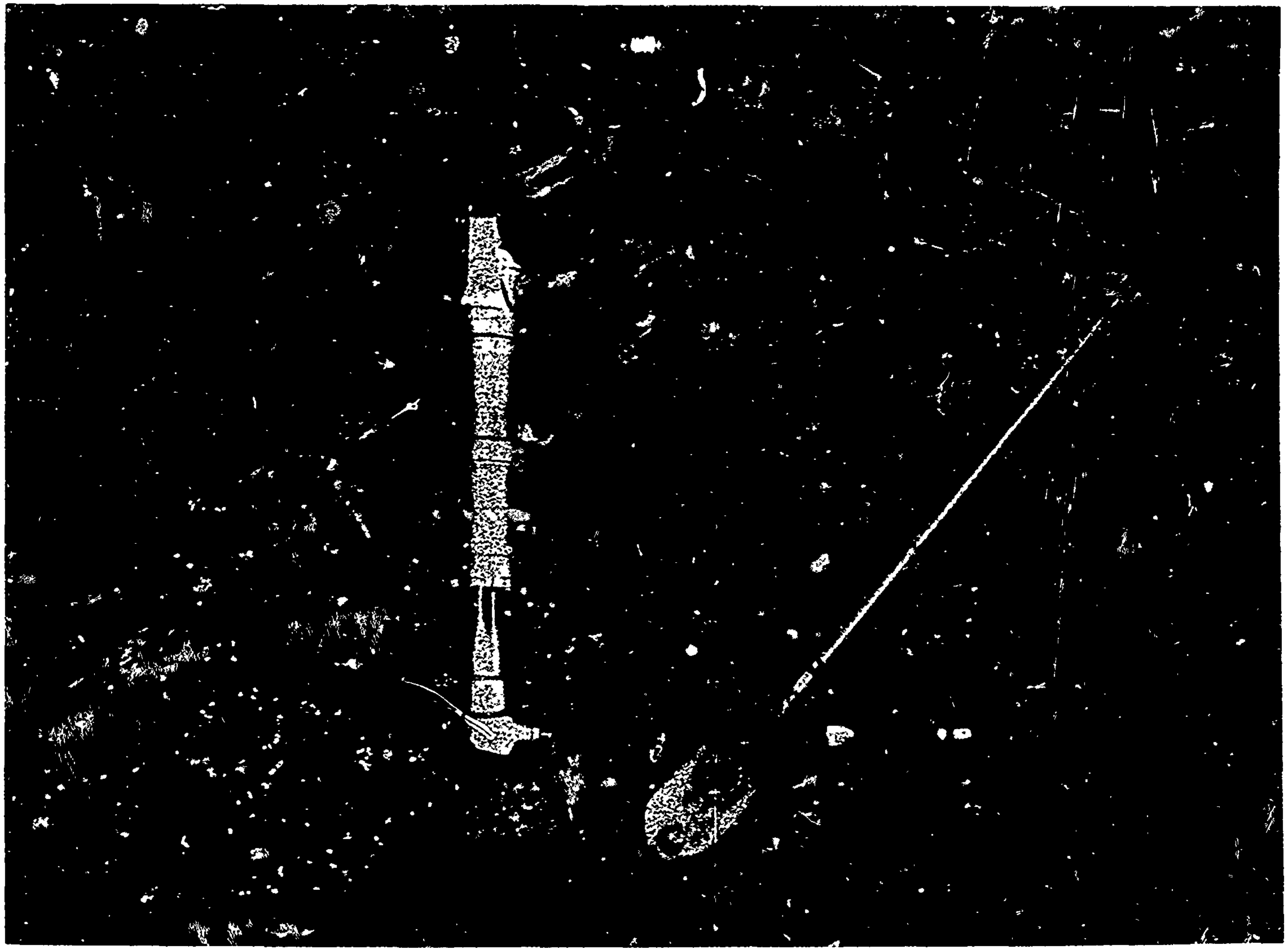
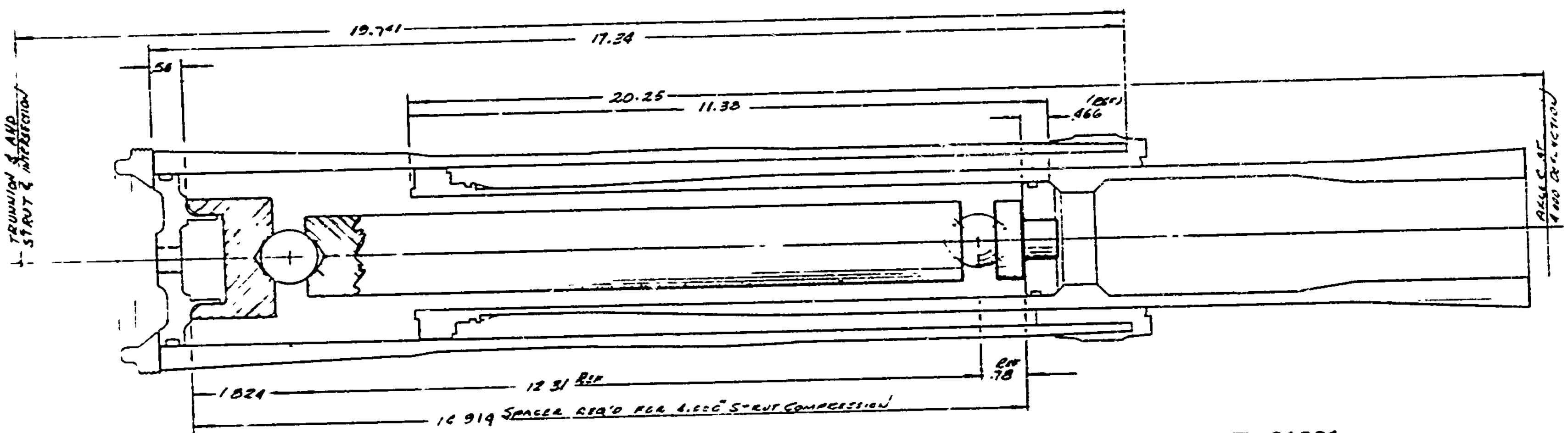


Figure 7-12. Filament Composite Landing Gear Assembly in Loading Rig (P-25175A)




Ref. VXD-31221

Figure 7-13. Piston Stroke Spacer

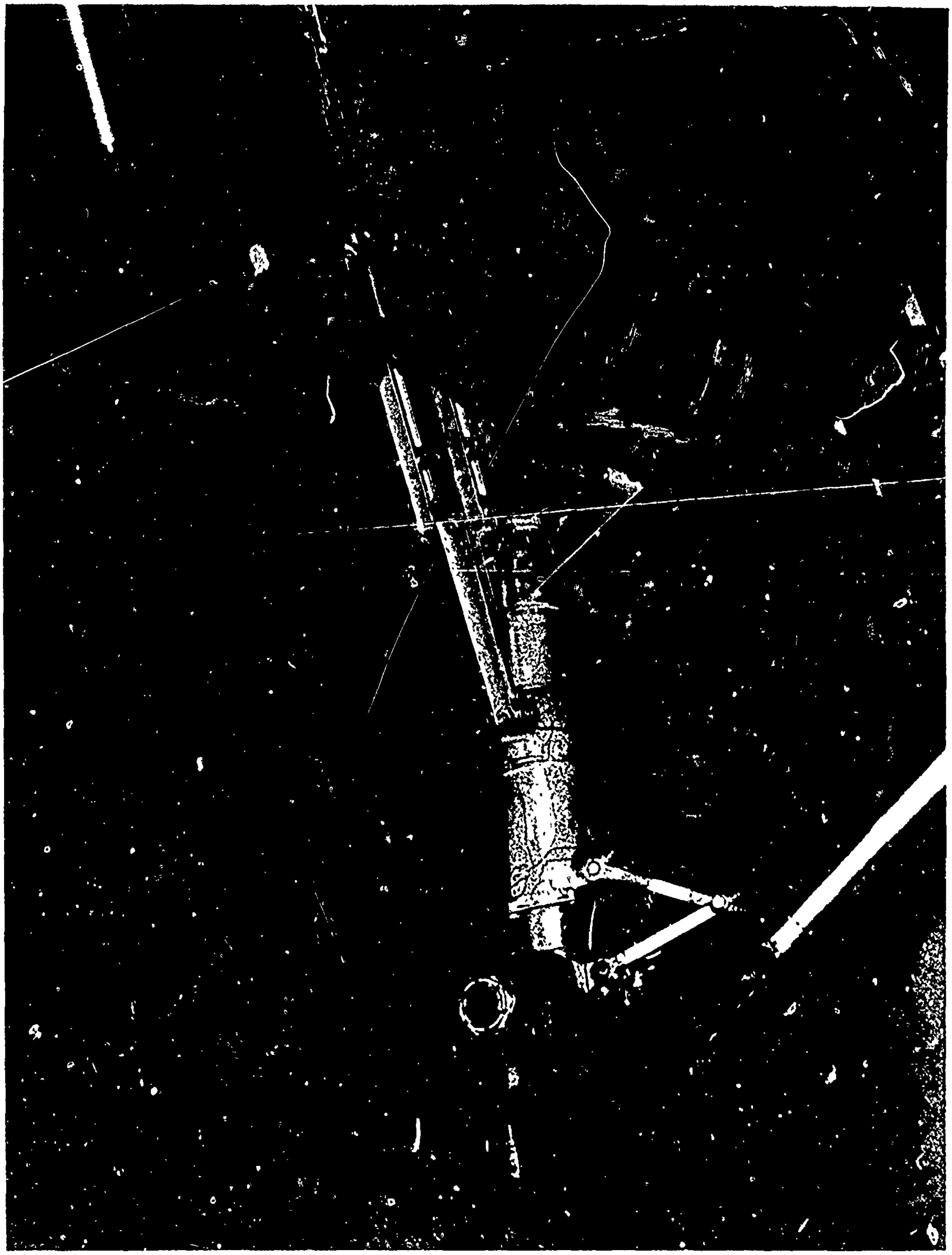


Figure 7-14. Shock Absorber Assembly After Test to 1/2 Limit Loads (P-25175I)

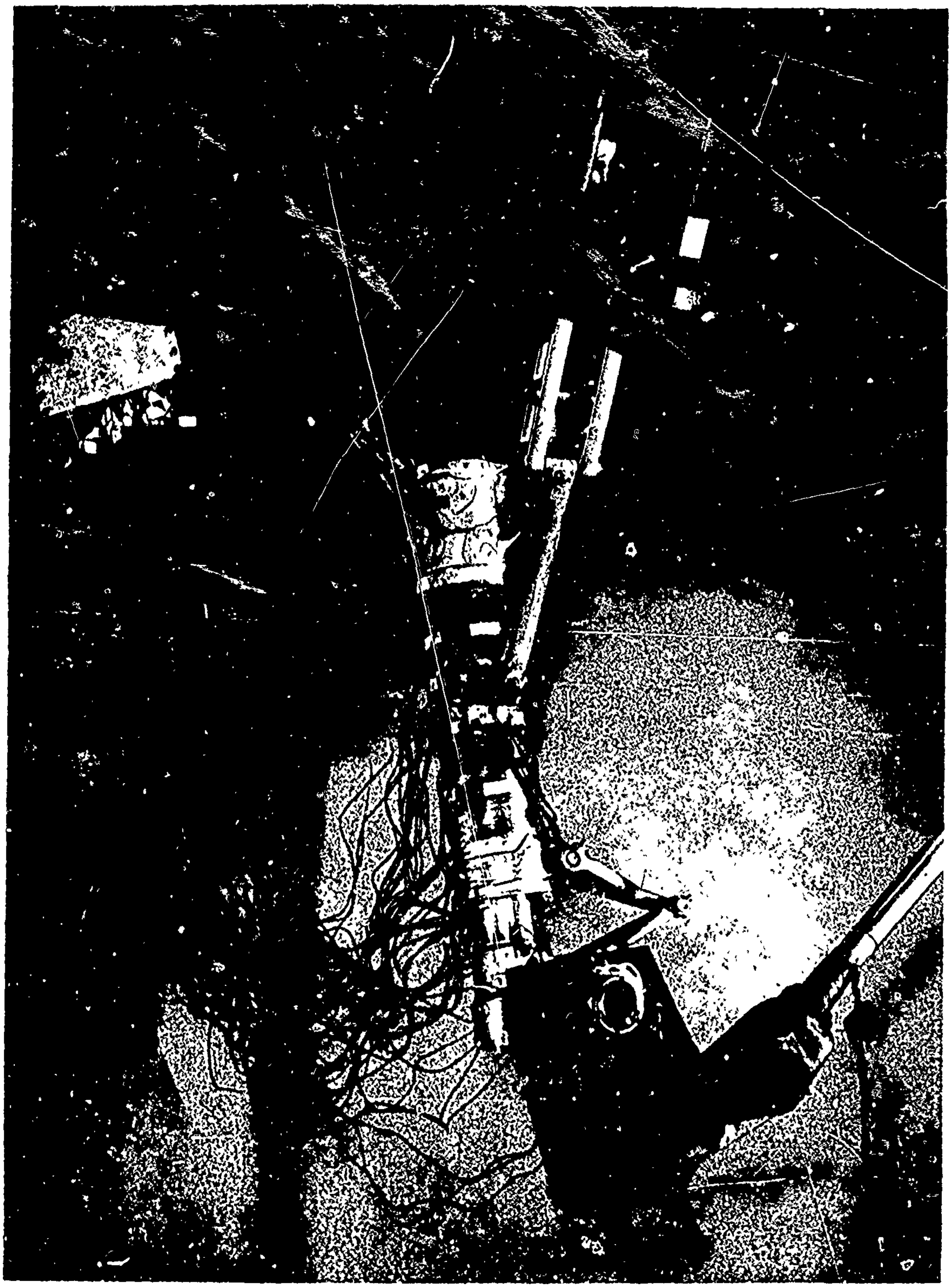


Figure 7-15. Shock Absorber Assembly with Strain Gage Applications (P-25175P)

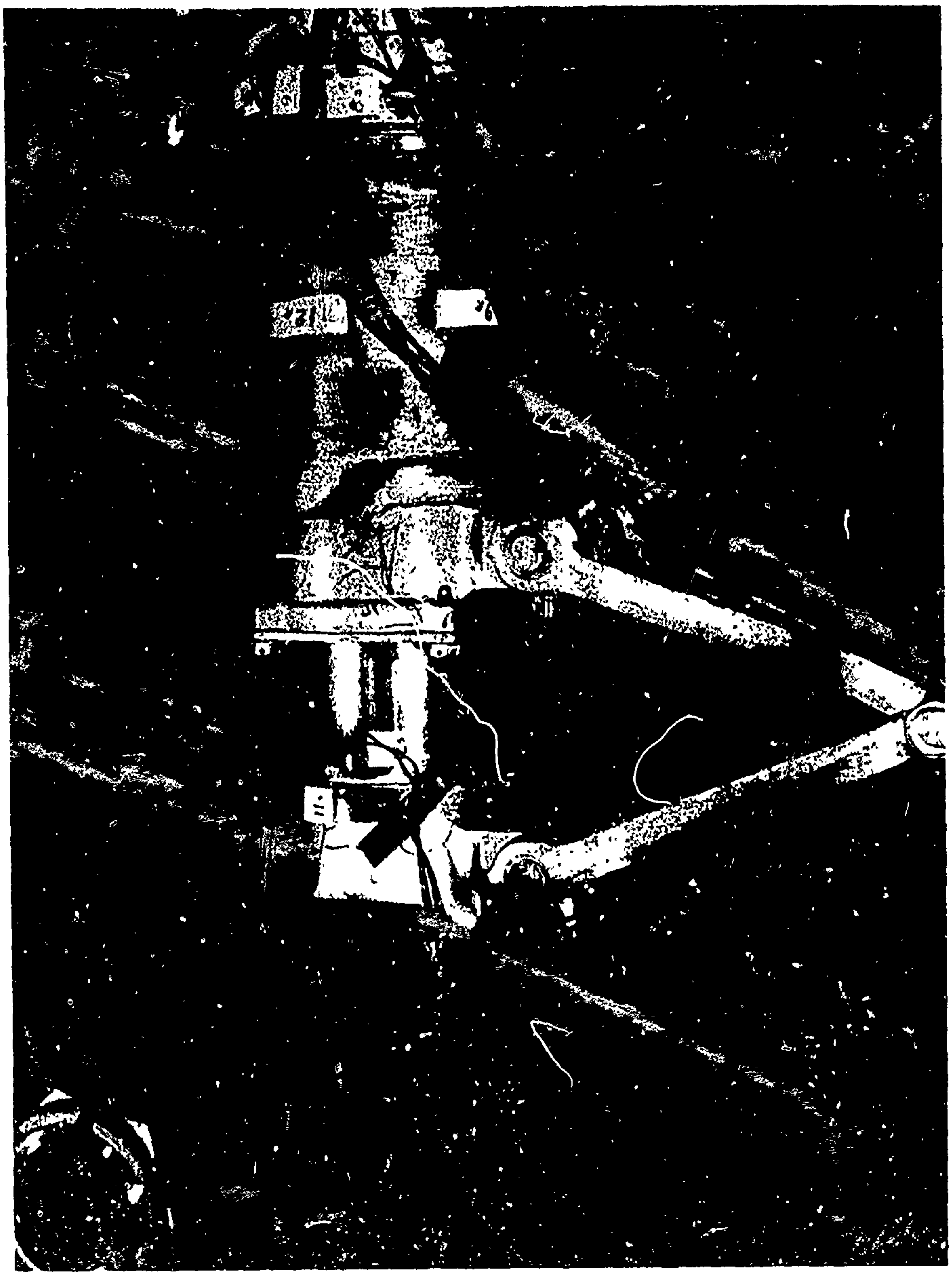


Figure 7-16. Failed Bond at Torque Arm Fitting (P-25175Q)

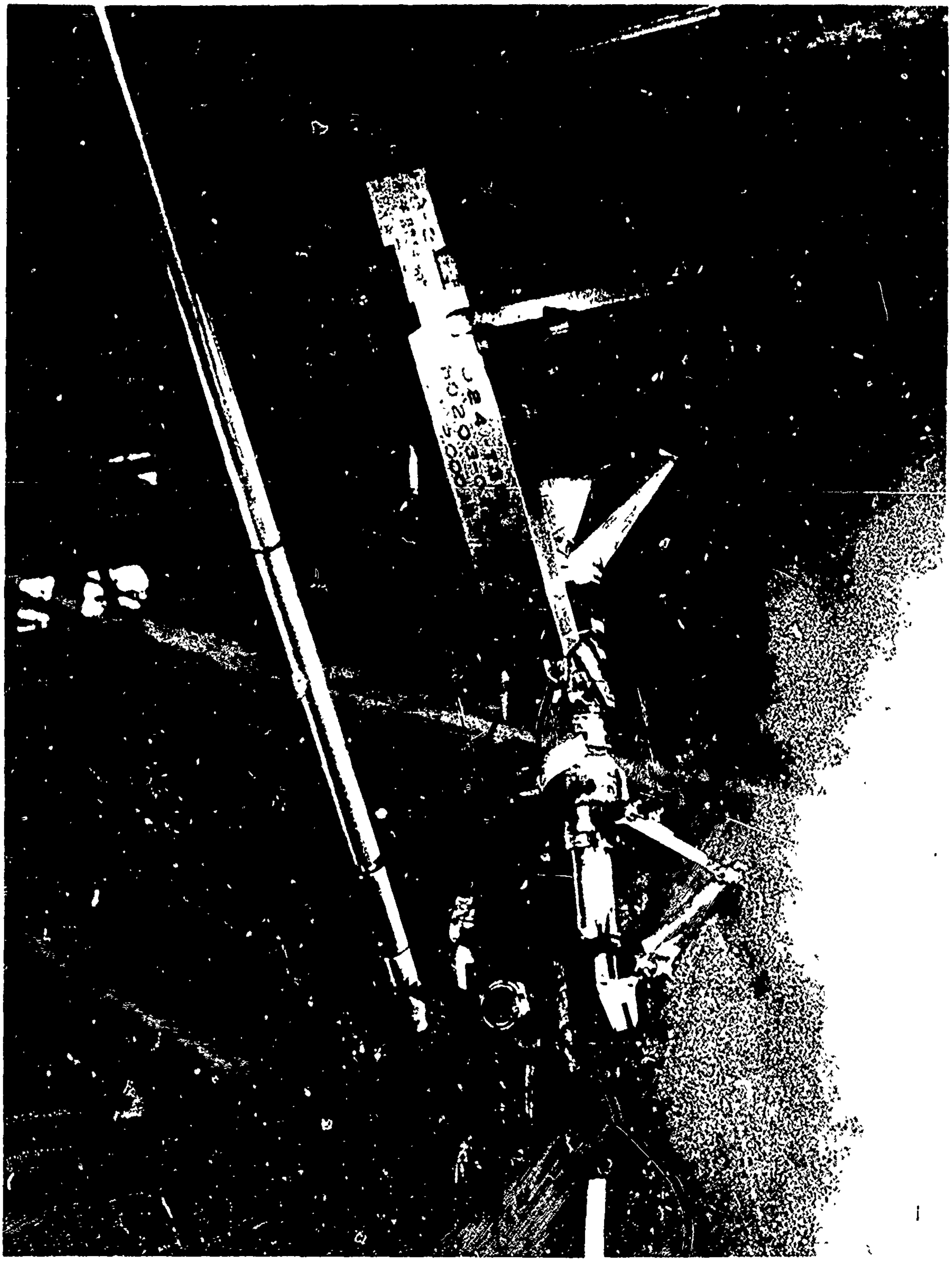


Figure 7-17. Simulated Side Brace Installation (P-25175BB)

Figure 7-18. Crack in Outer Cylinder Wall (P-25175Y)

Figure 7-19. Wrinkle in Nickel Liner (P-25175X)

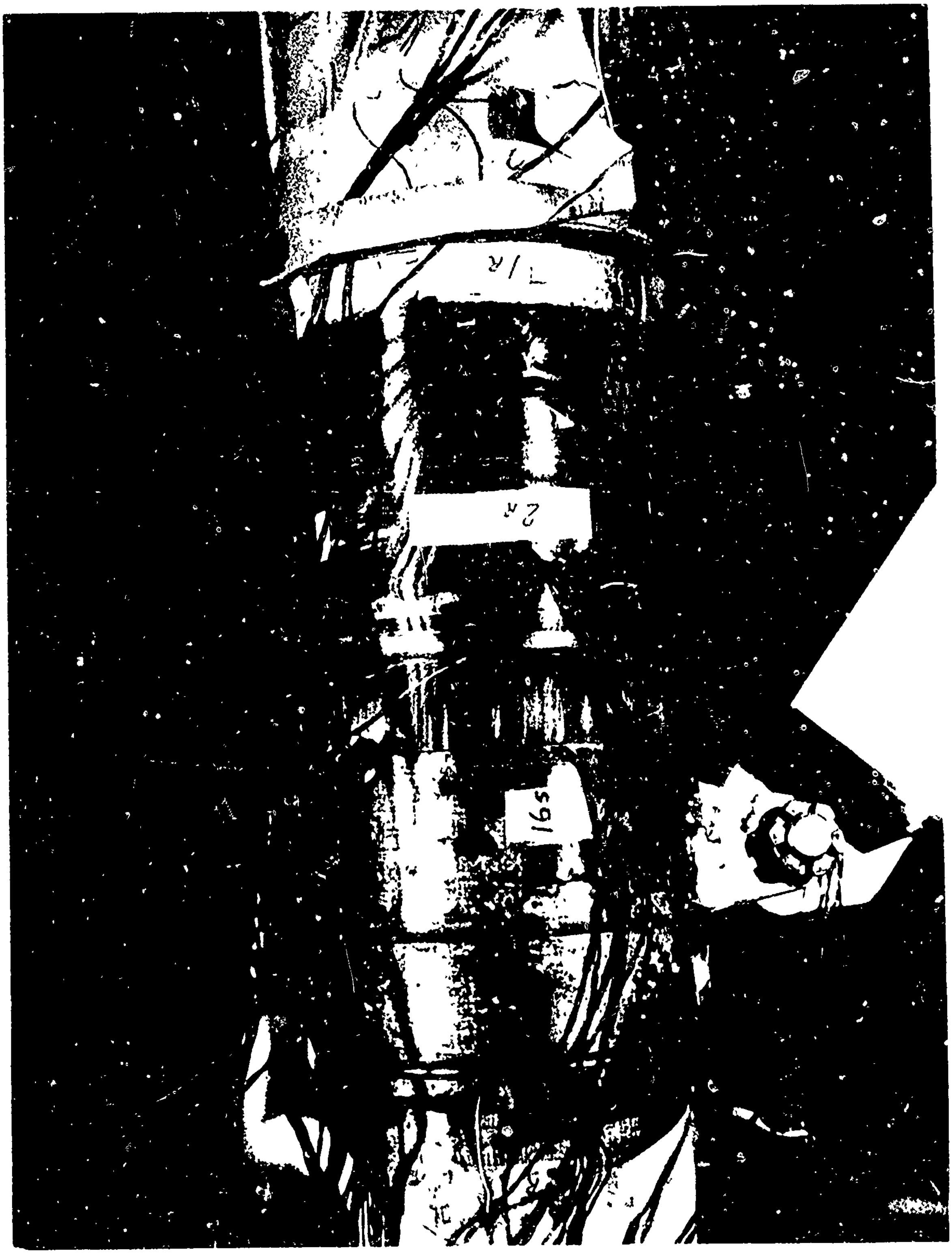



Figure 7-20. Failure of Glass Bond at Side Brace Fitting (P-25175Z)

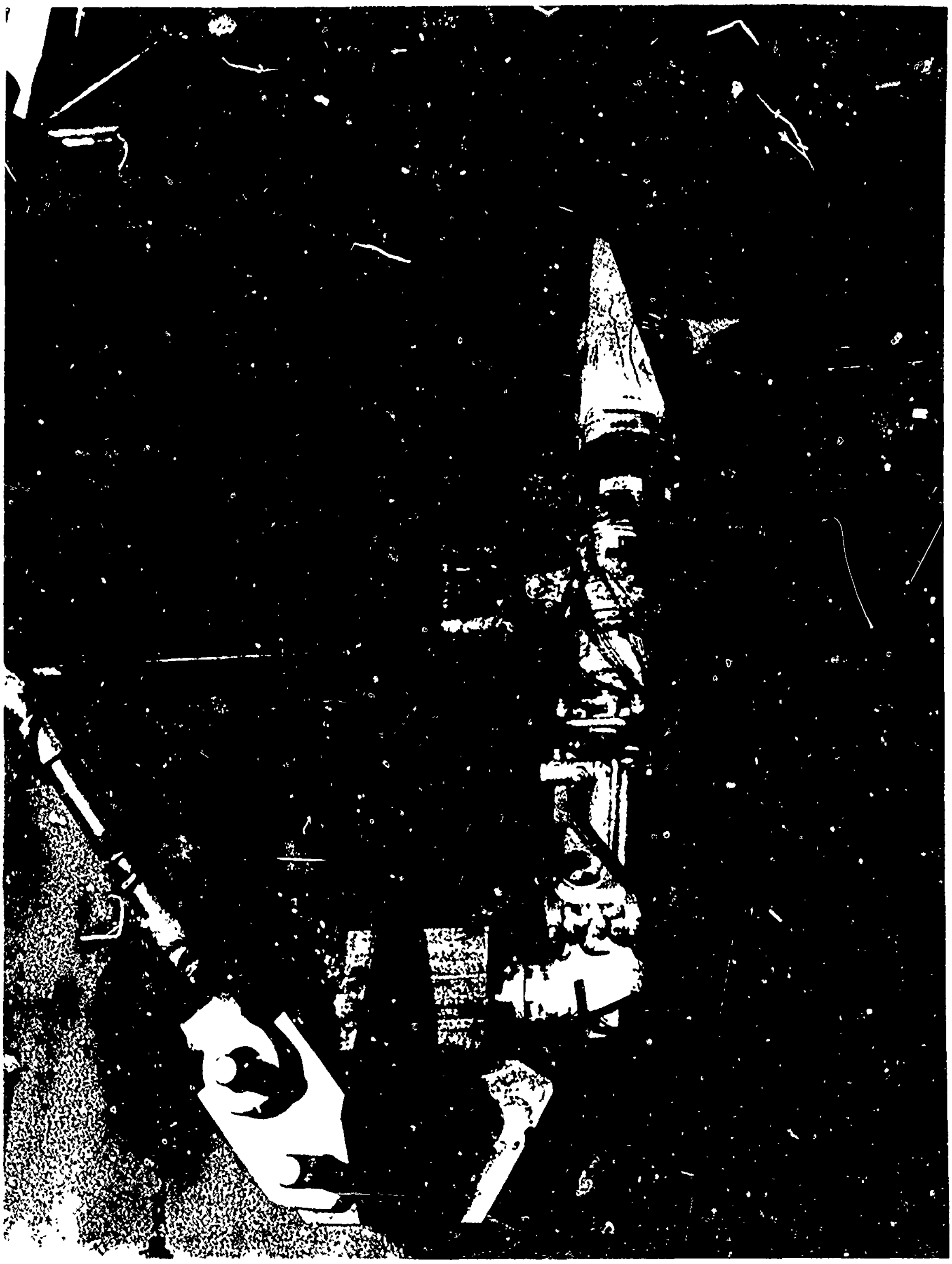


Figure 7-21. Horizontal Side Brace Installation (P-25190)

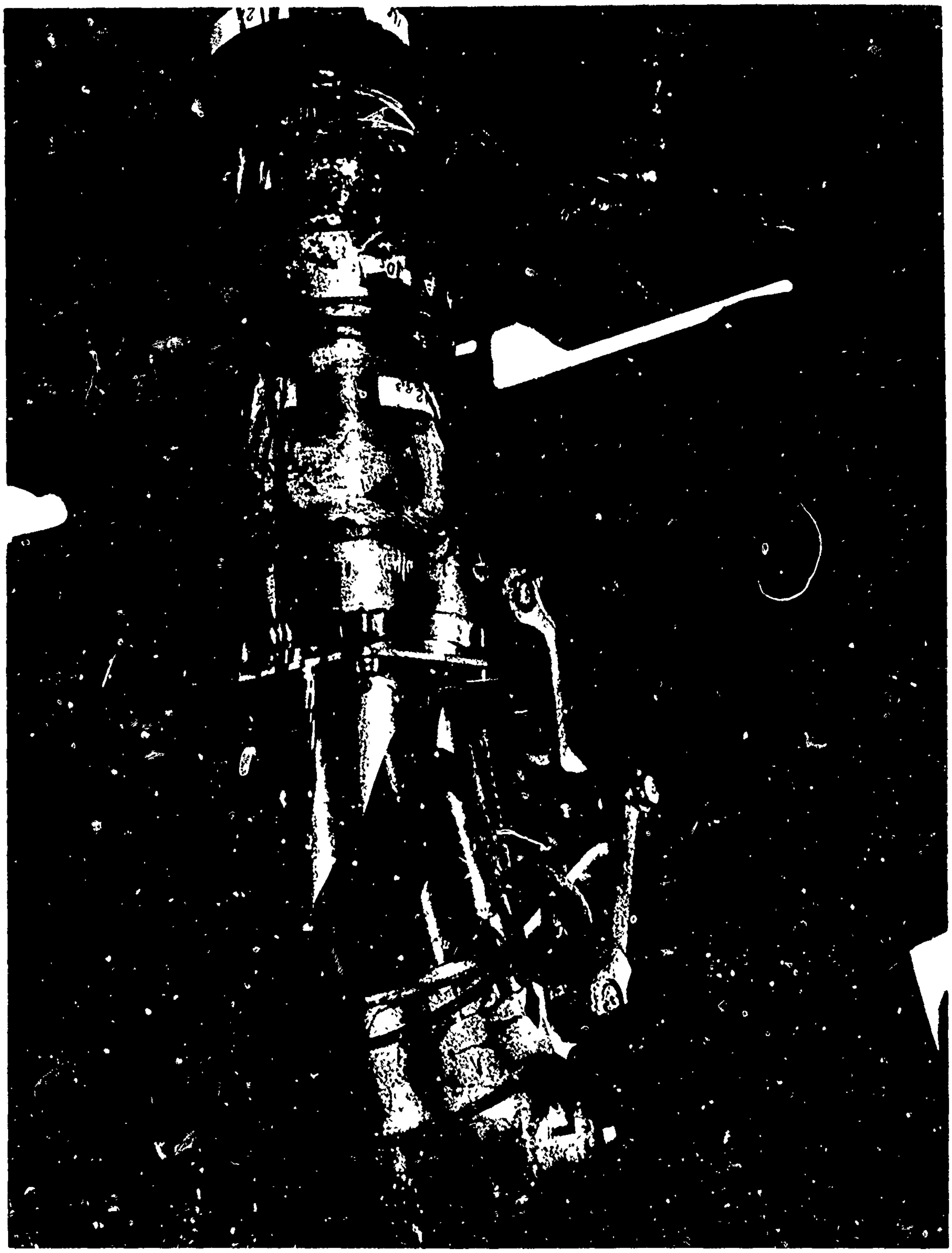


Figure 7-22. Ruptured Piston (P-25190A)

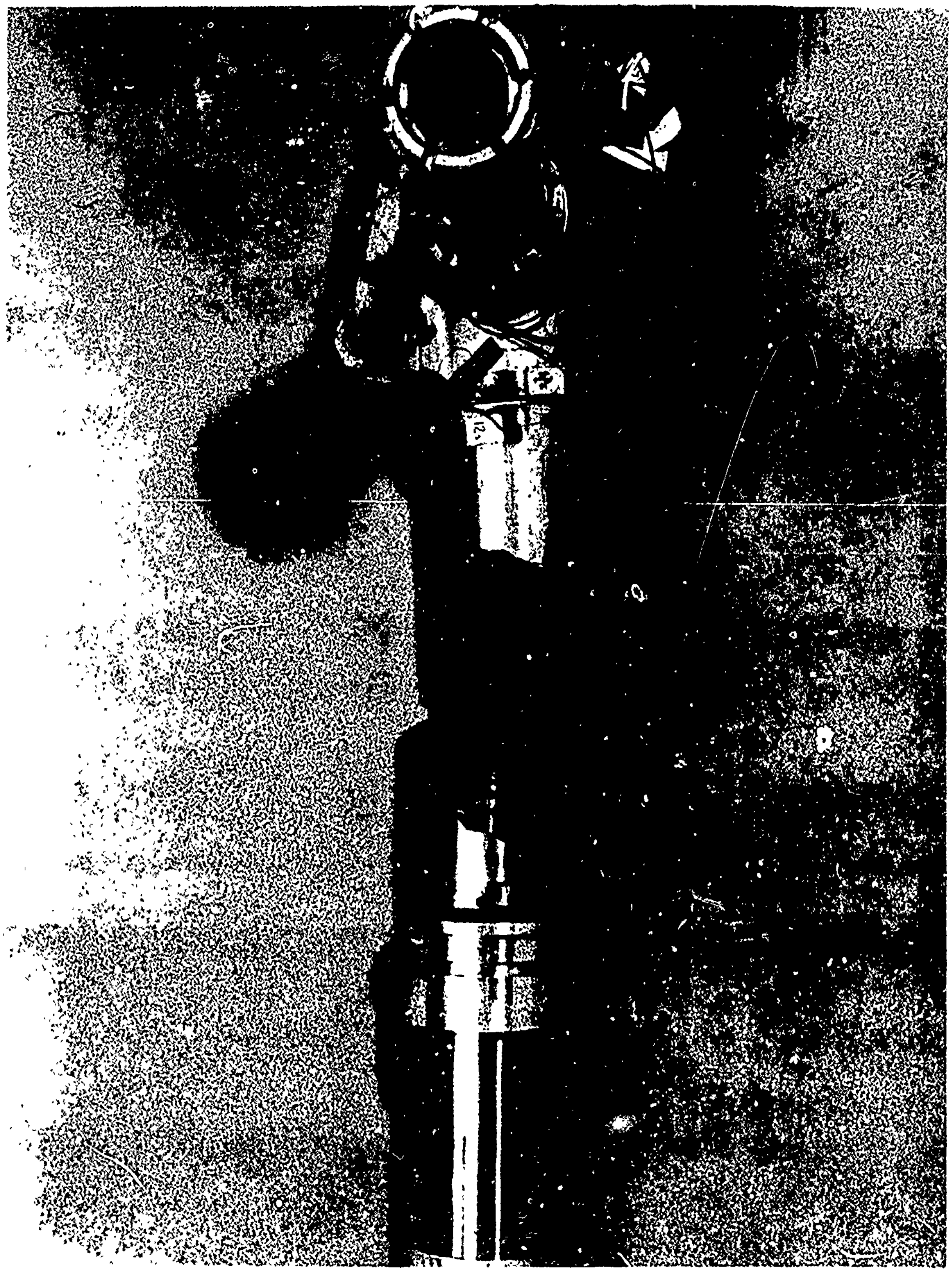


Figure 7-23. Ruptured Piston (P-25190G)

Figure 7-24. Simulated Piston (P-25190T)

Figure 7-25. Simulated Piston Setup (P-25190K)

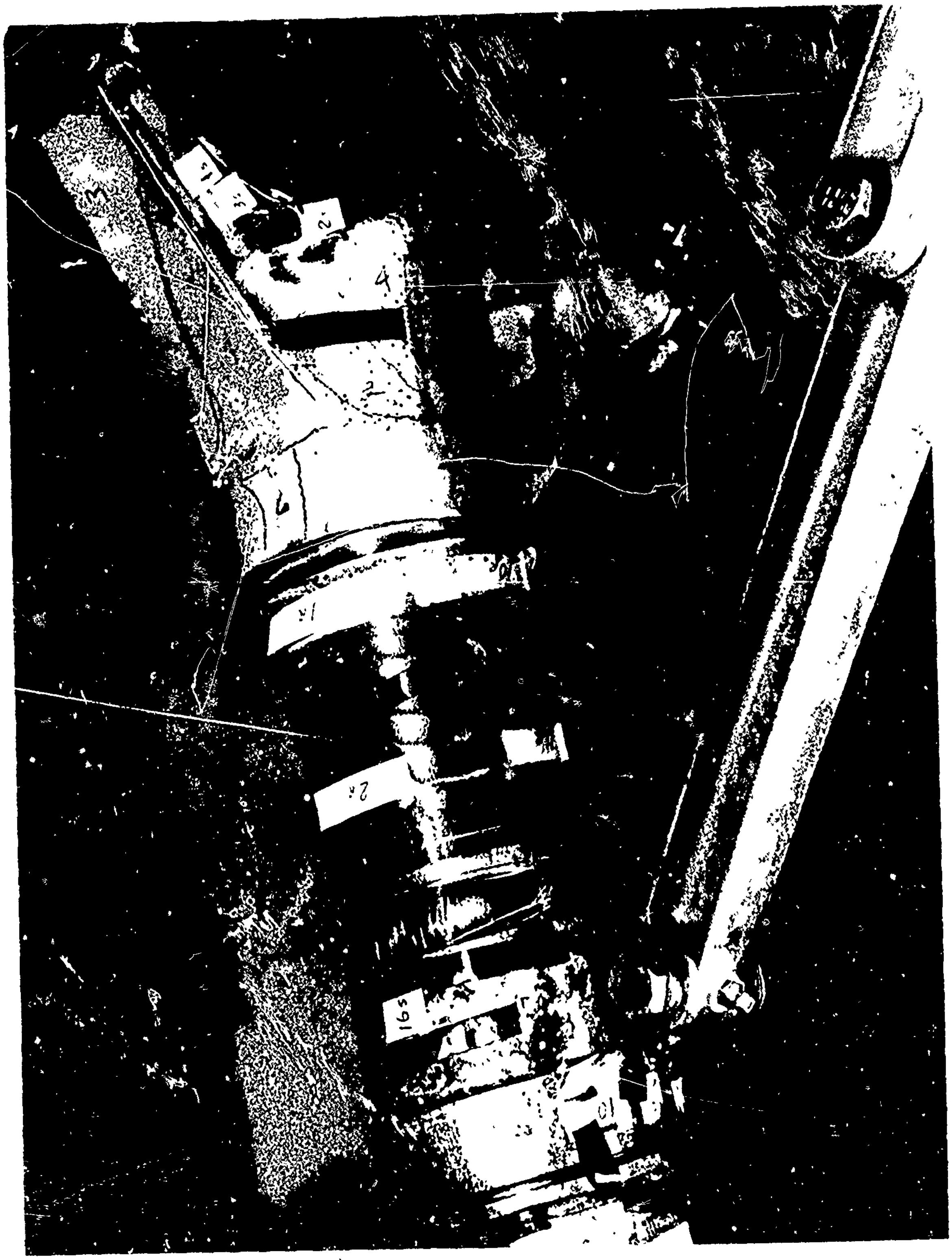


Figure 7-26. Ruptured Outer Cylinder (P-25190L)

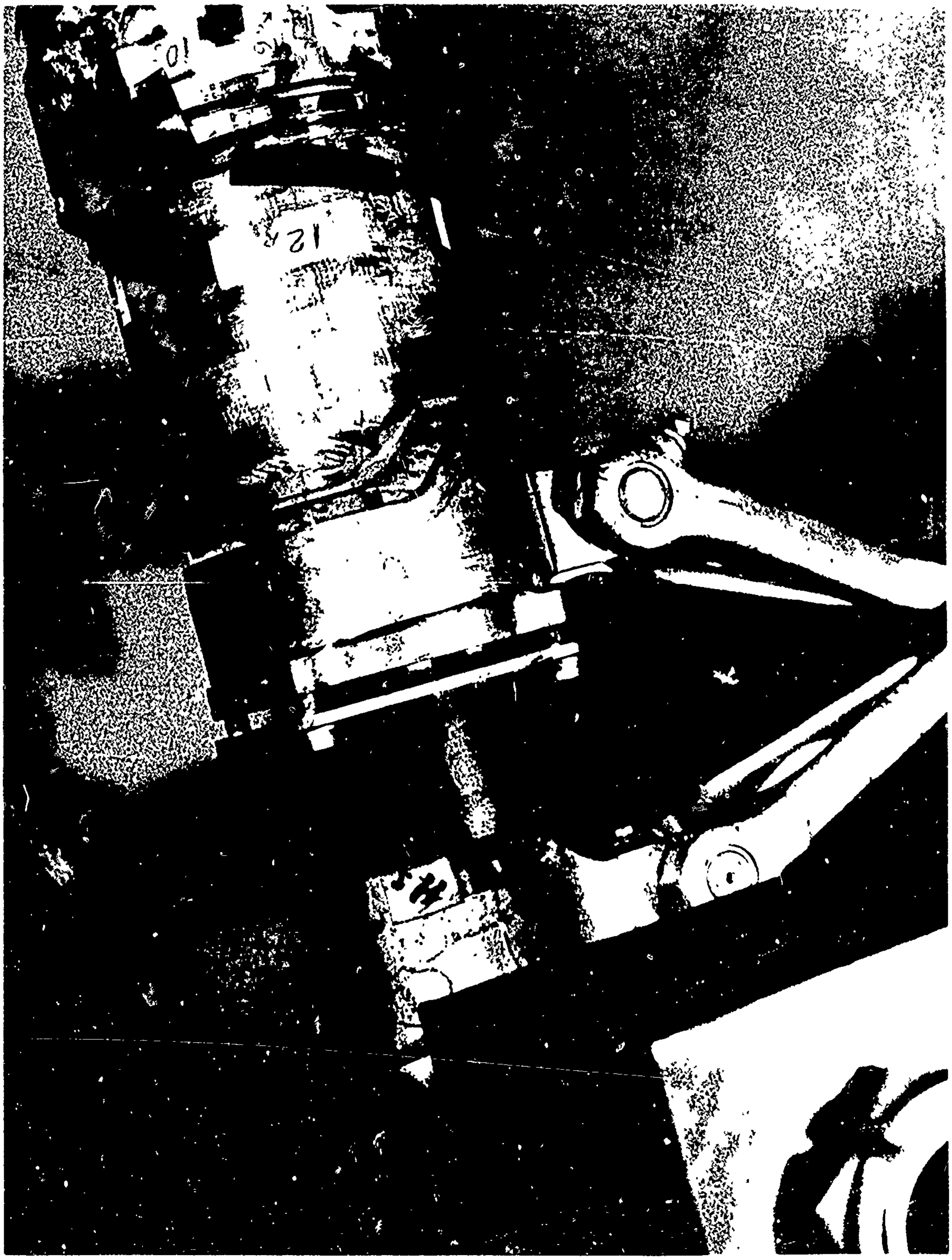


Figure 7-27. Failed Bond at Torque Arm Fitting (P-25190M)

Figure 7-28. Failed Outer Cylinder (P-25190S)

#### 7.2.2.2 Side Brace Test

As discussed earlier in this section, the side brace was tested as a separate component rather than as part of the landing gear assembly. Critical design loads are axial so the brace was tested in an MTS universal loading machine. The design limit loads are

| | | |
|---|---|---|
| Tension | - | 9,000 pounds |
| Compression | - | 20,000 pounds |

The brace was tested in two stages. In Stage 1, the brace was tested as an assembly combining the upper and lower links, Figure 7-29. Loading was increased until failure occurred at the lower end of the upper links during compression loading, Figure 7-30. During Stage 2, loads were applied to the lower link which was still structurally intact after the previous failure, Figure 7-31. This member sustained a failure during compression loading, Figure 7-32.

##### Stage 1

A summary of loads applied during Stage 1 and the measurements taken are given in Table 7-3.

The side brace was covered (sprayed) with Stresscoat lacquer. The purpose of the Stresscoat covering was to assist in determining regions of highest strain for later application of strain gages. As indicated by Table 7-3, the Stresscoat survey was accomplished during loadings 1, 2 and 3. Strain gage data was collected during various loadings as indicated by the table. The analysis of the strain gage results is given in Appendix G.

Deflection gages were applied to measure lateral deflections at the center hinge pin during compression loading.

Loads 1 through 5 were a series of compression loadings, Table 7-3. The brace was supported as a pin ended column with no lateral supports between the end pins. Loading and unloading was done in a continuous manner, except for load 3 which was applied in increments in order to record strain gage output.

Hinge pin deflections were measured for loadings 4 and 5. These deflections are shown plotted against load in Figure 7-33, curve labelled "no lateral support."

Tension was applied to the brace assembly during loadings 6 and 7. The loads were applied in increments in order to record strain gage data. A load level of 100 percent of design limit was achieved without apparent damage to the structure.

Prior to the application of further compression loadings, an analysis was made of the lateral hinge pin deflections measured during loadings 4 and 5. The deflections plot, Figure 7-33, indicated that with the brace supported as a simple pin ended column, excessive deflections would be experienced at the higher loads, which would lead to premature collapse. It was therefore decided to install the lateral support illustrated in Figure 7-29. This support simulates the aircraft installation which includes a landing gear extension downlock mechanism which attaches to the side brace at this location.

Compression loadings 8 through 9, Table 7-3, produced the hinge pin deflections plotted in Figure 7-33 and labelled "lateral support." It is apparent that considerably less lateral deflection was experienced with the lateral support installed.

All loads were applied continuously except load 8 which was applied in increments in order to record strain gage data.

A compression load level of 98 percent design limit was reached when failure of both upper links was experienced at a location just above the hinge pin, Figure 7-30. Failure was due to rupture of all four boron-epoxy flanges. Failure was attributed to excessive deflections of the hinge pin which caused the axial loading to shift toward the inner edges of the flanges.

## Stage 2

After failure of the upper links, a visual examination revealed no apparent structural damage to the lower link. It was therefore decided to continue testing to determine the structural capacity of this link as an individual member. The test setup is illustrated in Figure 7-31.

Tension Load - A 9200 pound tension load (100 percent limit) was applied with no perceiveable damage. This load was successfully applied previously (load 7, Table 7-3) and was repeated as a proof load which might indicate structural damage resulting from Stage 1 loading.

Compression Load - The link was loaded continuously until failure occurred at 23000 pounds (115 percent limit load). The failed part is illustrated in Figure 7-32. The failure appeared to initiate in the metal end fitting as a shear failure and with rupture of the boron composite flange as a secondary failure.

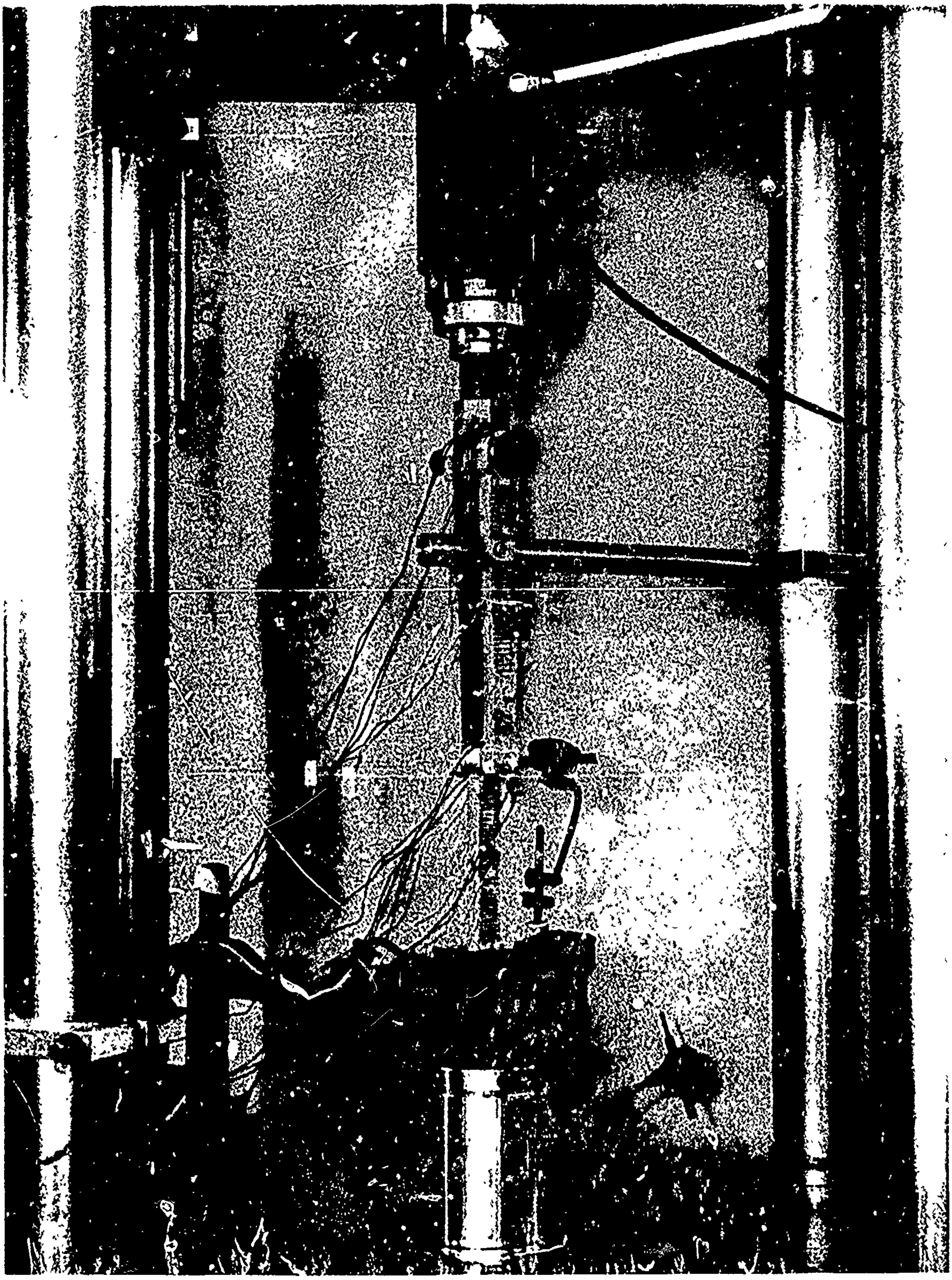


Figure 7-29. Side Brace Assembly in Test Machine (P-25190C)

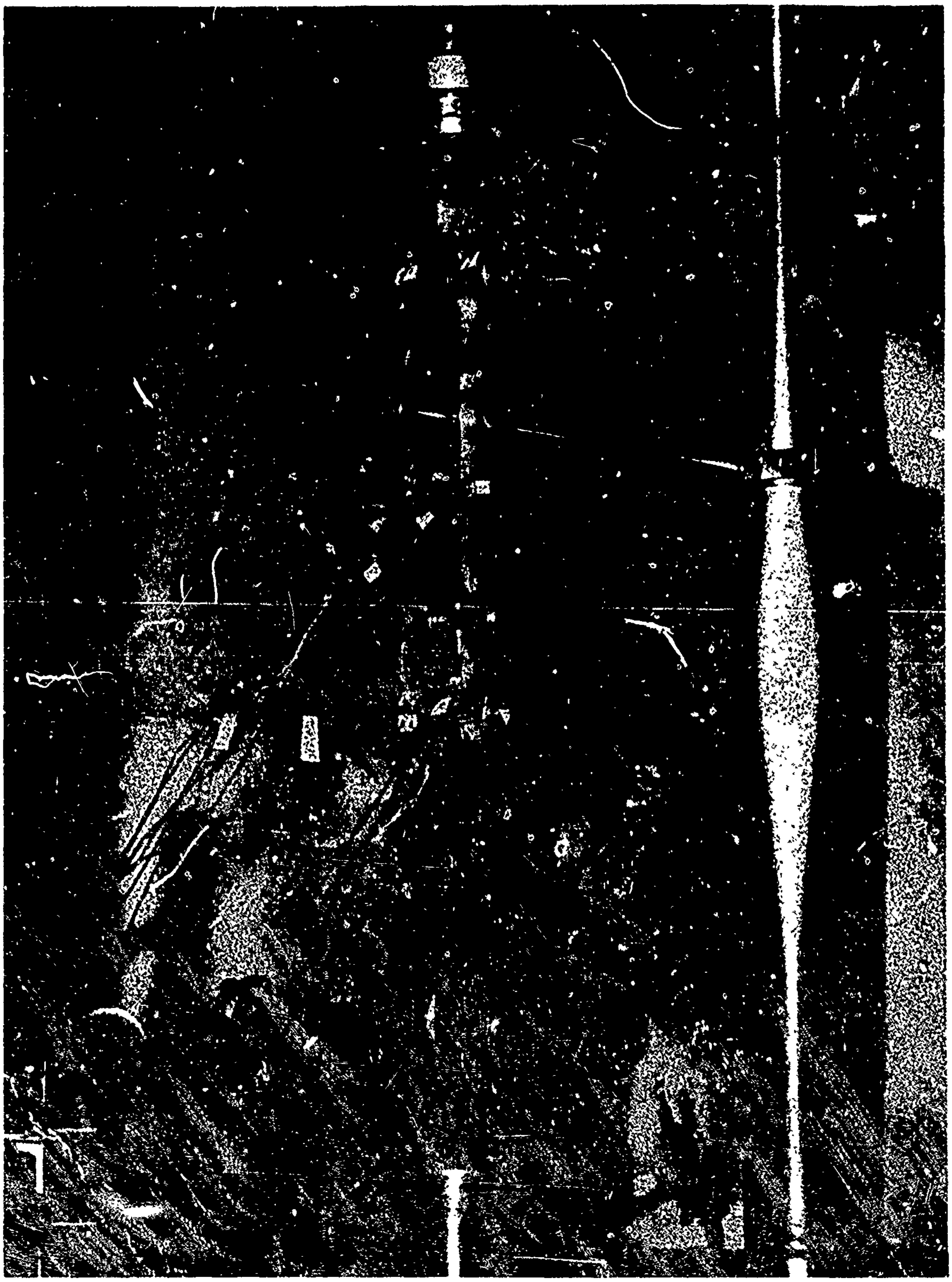


Figure 7-30. Failed Side Brace Assembly (P-25190J)

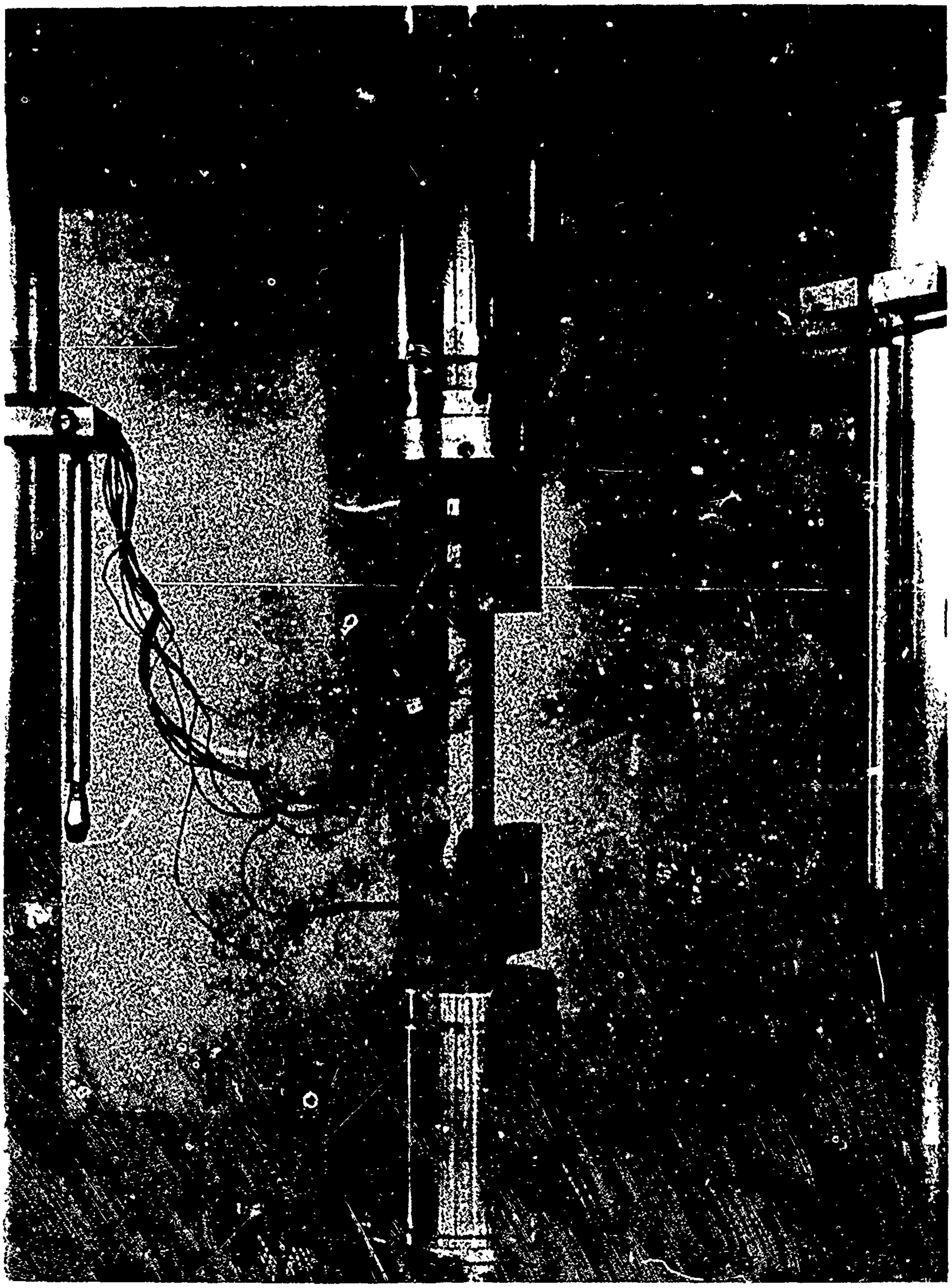


Figure 7-31. Side Brace Lower Link in Test Machine (P-25190B)

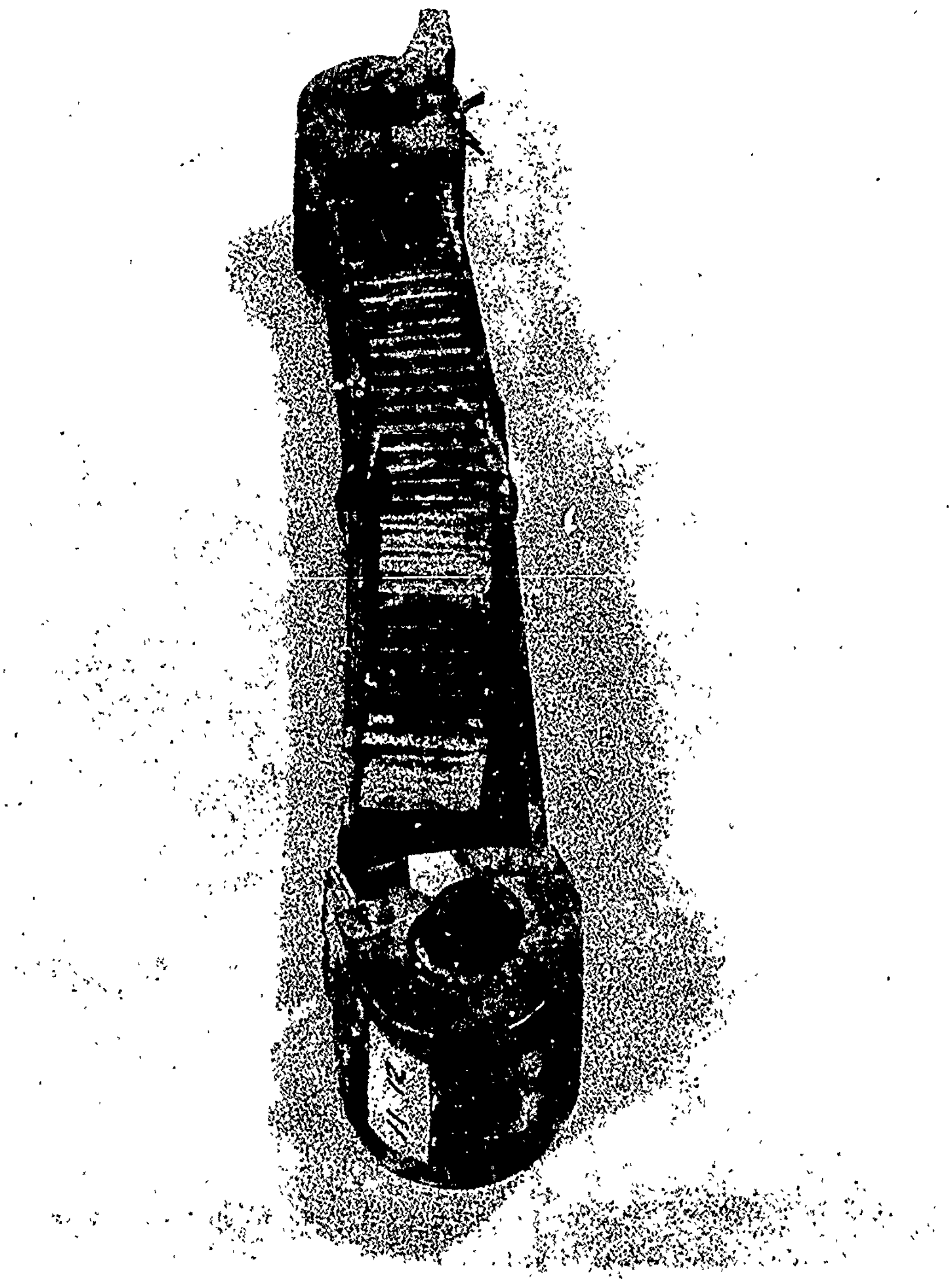


Figure 7-32. Failed Side Brace Lower Link (P-25190U)

TABLE 7-3. LOAD SUMMARY SIDE BRACE ASSEMBLY

| Load Sequence | Load, Kips* | % Limit | Stress Coat | Strain Gages | Deflection Gages | Lateral Support |
|---|---|---|---|---|---|---|
| 1 | -2 | 10 | X | | | |
| 2 | -4 | 20 | X | | | |
| 3 | -6 | 30 | X | X | | |
| 4 | -6 | 30 | | | X | |
| 5 | -10 | 50 | | | X | |
| 6 | +4.6 | 50 | | X | | |
| 7 | +9.2 | 100 | | X | | |
| 8 | -8 | 40 | | X | X | X |
| 9 | -6 | 30 | | | X | X |
| 10 | -10 | 50 | | | X | X |
| 11 | -15 | 75 | | | X | X |
| 12 | -18 | 90 | | | X | X |
| 13 | -19.6 | 98 | | X | X | X |

* + tension, - compression

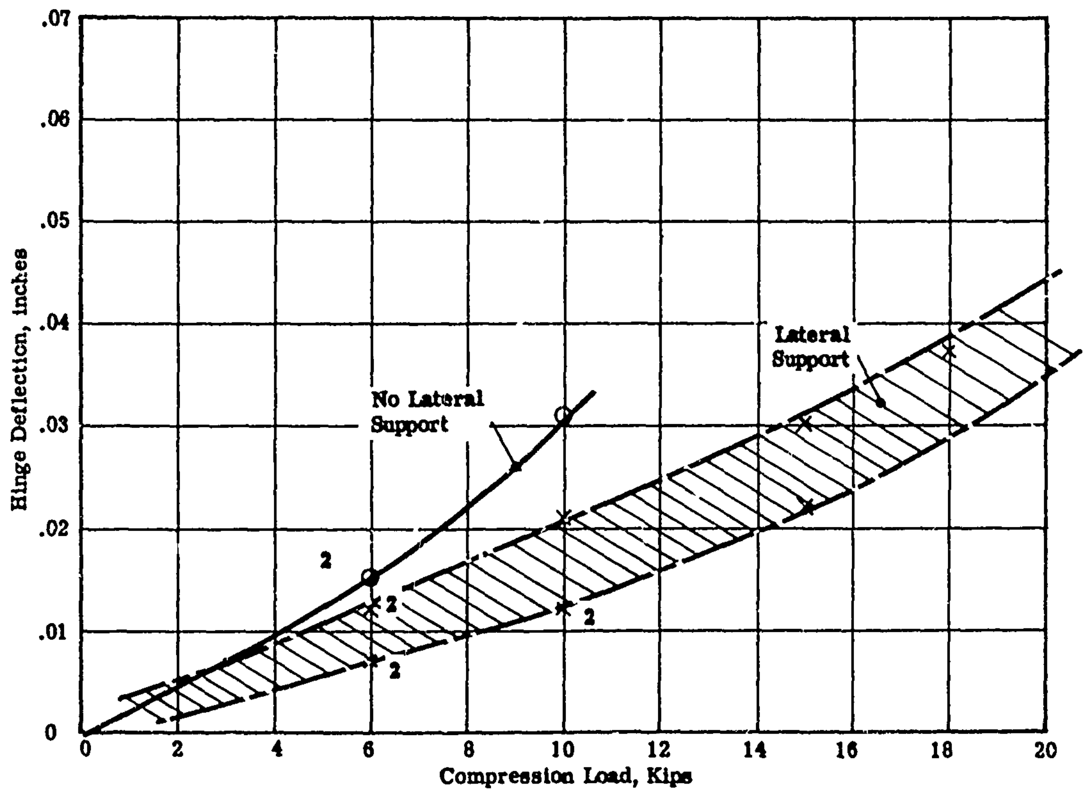



Figure 7-33. Side Brace Hinge Deflections

## 7.3 PERFORMANCE REVIEW - CONCLUSIONS AND RECOMMENDATIONS

### 7.3.1 Shock Absorber

#### 7.3.1.1 Leakage and Fluid Containment

During the various pressure tests the shock absorber components were subjected to the following internal pressure history.

| Pressure | Time |
|---|---|
| 90 psi | 16 hours |
| 400 psi | 24 hours |
| 2650 psi | 15 minutes (piston only) |

During these tests, no problems were apparent with respect to leakage of the seals or seepage of hydraulic fluid through the cylinder walls. This performance was exhibited in spite of the lack of the piston ID nickel liner.

Longer term and more detailed tests would be required to determine the effects of hydraulic fluid on the composite materials.

#### 7.3.1.2 Structural Design

1. Integrally Wound Shoulder - Figures 5-91 and 5-92 illustrate the metering pin diaphragm support which was wound integrally as part of the piston cylinder. An alternate would have been a separate cylindrical support extending to the axle center line which would have resulted in additional weight and expense.

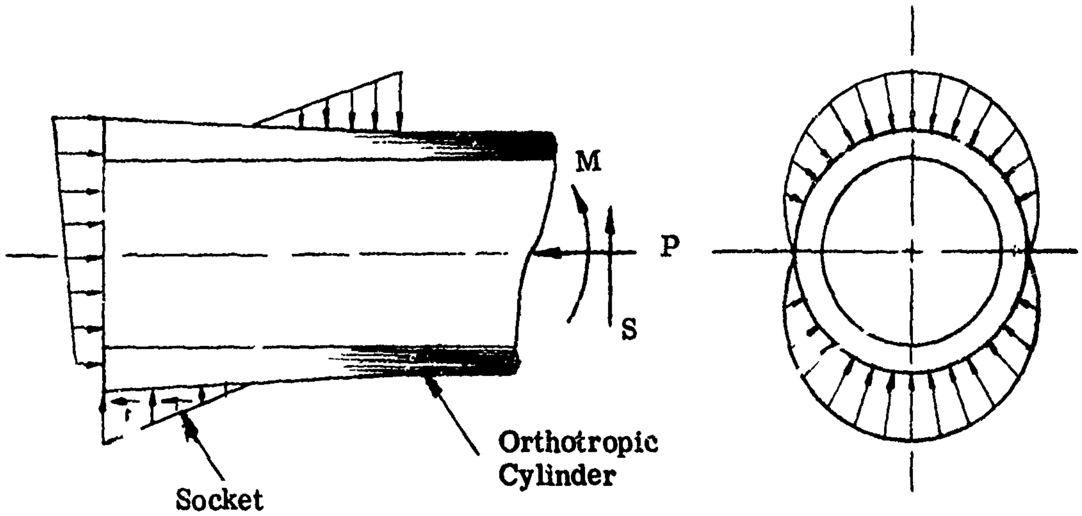
The structural tests performed during this program have indicated the feasibility of filament wound load carrying shoulders as an integral part of the cylinder wall.

2. Socket Joint - Two socket joints were used in the landing gear design as primary structural attachments, one between the piston and axle and the other between the outer cylinder and the trunnion. These socket joints were required to support high bending loads. Applications of the socket concept used are illustrated in Figures 5-69, 5-73, 5-80, 5-90 and 5-95.

A reverse taper of the socket was incorporated to resist the tendancy of the mating parts to separate.

In every case the load was supported without actual joint separation. Where failure occurred, it was due to rupture of the composite inner member, not by joint separation.

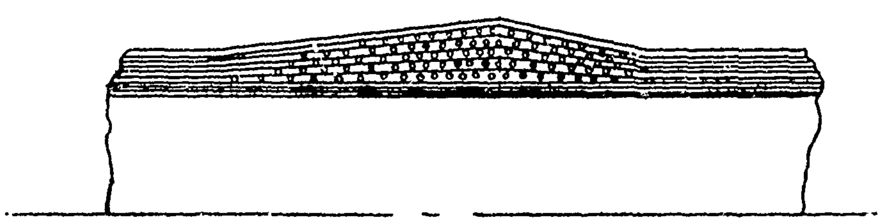
The test program established the feasibility of this type of joint for carrying high intensity loads. However, more work is required in developing a detailed analysis procedure for this type of attachment to improve the reliability of joint design. The following illustration indicates a simplified model of the loading which should be investigated and for which the resulting stresses in the cylinder must be determined.




3. Side Brace Fitting - This fitting assembly is illustrated in Figures 5-80 and 5-81. This concept relies on the tapered build-up of the cylinder outer surface to react load components parallel to the cylinder axis.

During testing the fitting showed a tendency to slip on the glass build-up. It is believed that the design relied too much on friction for load resistance and that the taper angle should be increased. After bonding the fitting to the glass overwrap with Epon 934 cement, no further slip of the fitting with respect to the glass was noted.

Primary failure of this attachment occurred as a result of the separation of the glass overwrap from the boron cylinder, Figure 7-20. This indicates the desirability of a design which eliminates the weak interface between the conical build-up and the basic cylinder. Such a concept is illustrated schematically below.



The build-up is an integral part of the cylinder wall with uninterrupted filaments flowing continuously from the basic wall through the conical build-up. Circumferential filaments would be added to accommodate the increased thickness at this point. Contact forces from the fitting would flow along the continuous filaments directly into the cylinder wall without passing through an intervening weak bond surface.

The load intensity on this type of attachment is relatively low. The results of this design and test activity indicate that a successful joint is possible. First, this requires improved load transfer from the fitting to the composite surface. This may be accomplished by increasing the taper angle on the conical build-up, and also by increasing the adhesive friction between the two surfaces. Secondly, the tapered build-up must be strengthened by constructing it as an integral part of the cylinder.

4. Outer Cylinder Torque Link Attachment - Failure of this joint occurred at the bonded interface between the fitting and the composite cylinder (Figure 7-27). The initial specification for this joint required an FM-1000 adhesive cured at 350°F (Figure 5-80). Phase I tests on similar joints indicated that this high strength adhesive is adequate for the purpose intended.

However, inspection of the composite cylinder revealed the presence of delamination flaws in the cylinder wall (Paragraph 8.2.5.2), and there was concern that subjecting the cylinder to the 350°F temperature might create distortions in the tube and further propagation of the flaws. Consequently a weaker cement, Epon 934, requiring a room temperature cure was used.

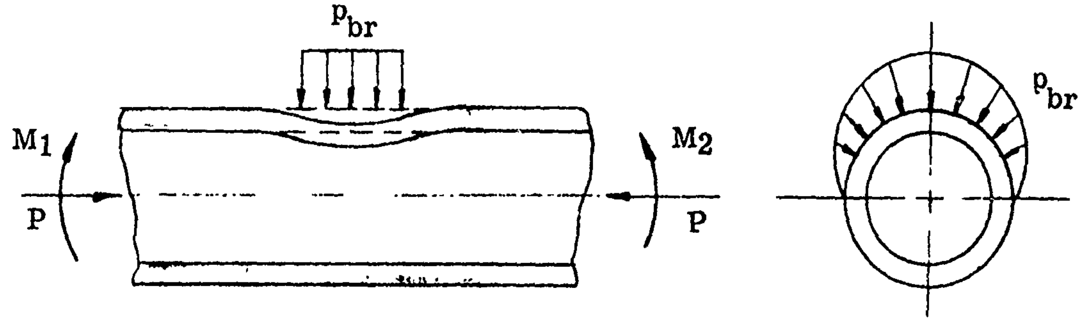
Two possible factors were seen as contributing to the premature failure of this joint. The first is the use of the weaker adhesive. The second is the cylinder wall delaminations which may have permitted cylinder distortions tending to promote separations of the mating surfaces.

Nevertheless, this joint did support 120 percent of limit load, and it is felt that with a cylinder of solid construction coupled with the bonding procedure originally specified, that a successful attachment is possible.

5. Bending Strength of Piston Cylinders - Two piston cylinders were tested during this program. The first test involved the trial specimen, Figures 5-97 and 5-98; the second test the prototype article, Figure 7-22. In both cases rupture of the cylinder coincided with the support bearing just above the cylinder-axle joint. The load levels achieved were 67 and 75 percent, respectively, of the target ultimate strength. Because of the ply separations which existed in the tubular products as received, it was not possible to determine whether the low load was due to a short coming in structural design or to the processing flaw. Nevertheless some comments concerning the structural design of a landing gear piston are useful.

The maximum value of the bending moment applied along the length of the piston cylinder coincides with the location of the lower bearing support mentioned above. Axial tension stresses are produced on the side of the cross section away from the support and compression on the near side. Since the strength of the boron laminate is considerably weaker in tension, the cylinder wall was designed by comparing the value of $Mc/I-P/A$ with the ultimate tensile strength of the laminate.

However, further consideration must be given to the possibility that the stresses are more critical on the compression side, particularly with respect to the contribution from the localized bearing load. This situation is illustrated by the simplified model below.




There is the prospect that the compression stresses due to local wall bending produced by the bearing pressure $p_{br}$ when combined with the compression stresses due to the nominal loads M and P may result in a more critical situation compared to material strength than on the tension side. Consideration of localized effects of this type is more important with composite construction than with the more ductile conventional materials. Further detailed analysis of this particular loading configuration appears warranted.

7.3.1.3 Cylinder Fabrication

Two primary difficulties were encountered with the fabrication of the cylinder products. One concerned adequate consolidation during the layup process. The other had to do with the accurate positioning of layup transitions.

1. Layup Consolidation - As indicated in Paragraphs 8.2.5 and 8.2.6, there were indications during the fabrication phase of ply separations in the cylindrical products. These were apparent by both visual and C-scan inspection. The existence of these flaws was confirmed by sectioning the cylinders after structural testing, Figures 7-34, 7-35, 7-36 and 7-37.

Such ply separations arise from difficulty in consolidating the circumferential and 45 degree plies during the layup operation. For a successful result, each ply must be compacted precisely into its prescribed radial position above the mandrel, while it is being laid down. One cannot rely on subsequent overwraps or ply applications to exert the necessary compaction on the layers below. Any loose circumferential or 45-degree filaments or plies will either bunch up and wrinkle, or fail to move from their original incorrect location, thus promoting delamination in the cylinder wall.

In order to produce thick-walled cylinders of sound structural quality from boron-epoxy materials, further development of layup techniques appears necessary.

2. Layup Transitions - In the design of the axle end of the piston tube, a ply transition arrangement was prescribed to provide a local reinforcement for carrying the concentrated loads imposed by the axle socket joint, Figures 5-90 and 5-92. This arrangement was intended to produce a ply layup which is parallel to the conical machined outer surface. This is required in order to provide uninterrupted paths of primary strength for the flow of contact surface stresses into the cylinder wall.

Examination of the piston cross section Figures 7-38 and 7-39 indicates that the internal ply surfaces along the outer edge are not parallel to the outside conical surface of the tube wall. This resulted in machining through the individual plys which then terminate at the outer surface rather than continue along and into the tube wall. This effect resulted from difficulty in accurately maintaining axial location of the ply transition points during the ply layup operation.

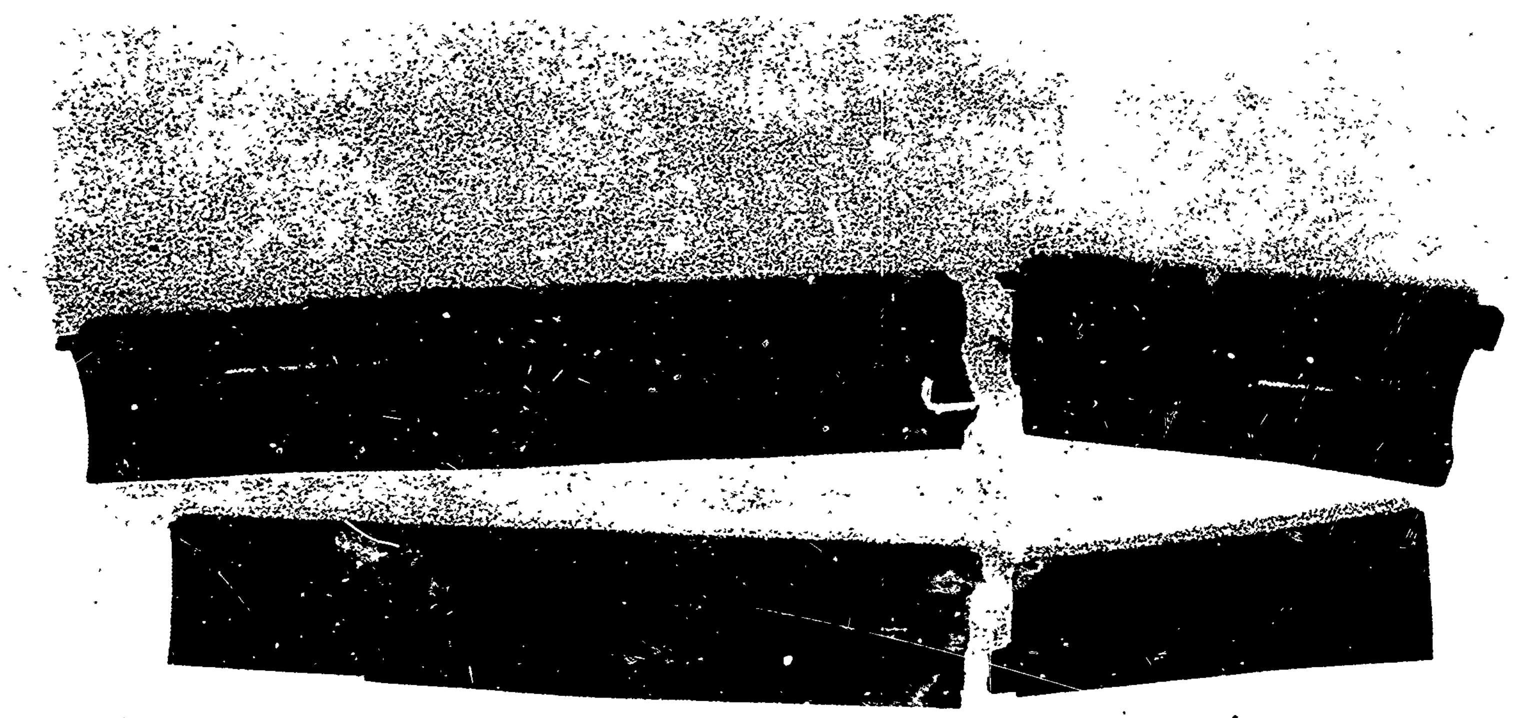


Figure 7-34. Sectioned Piston Cylinder (P-25190BB)

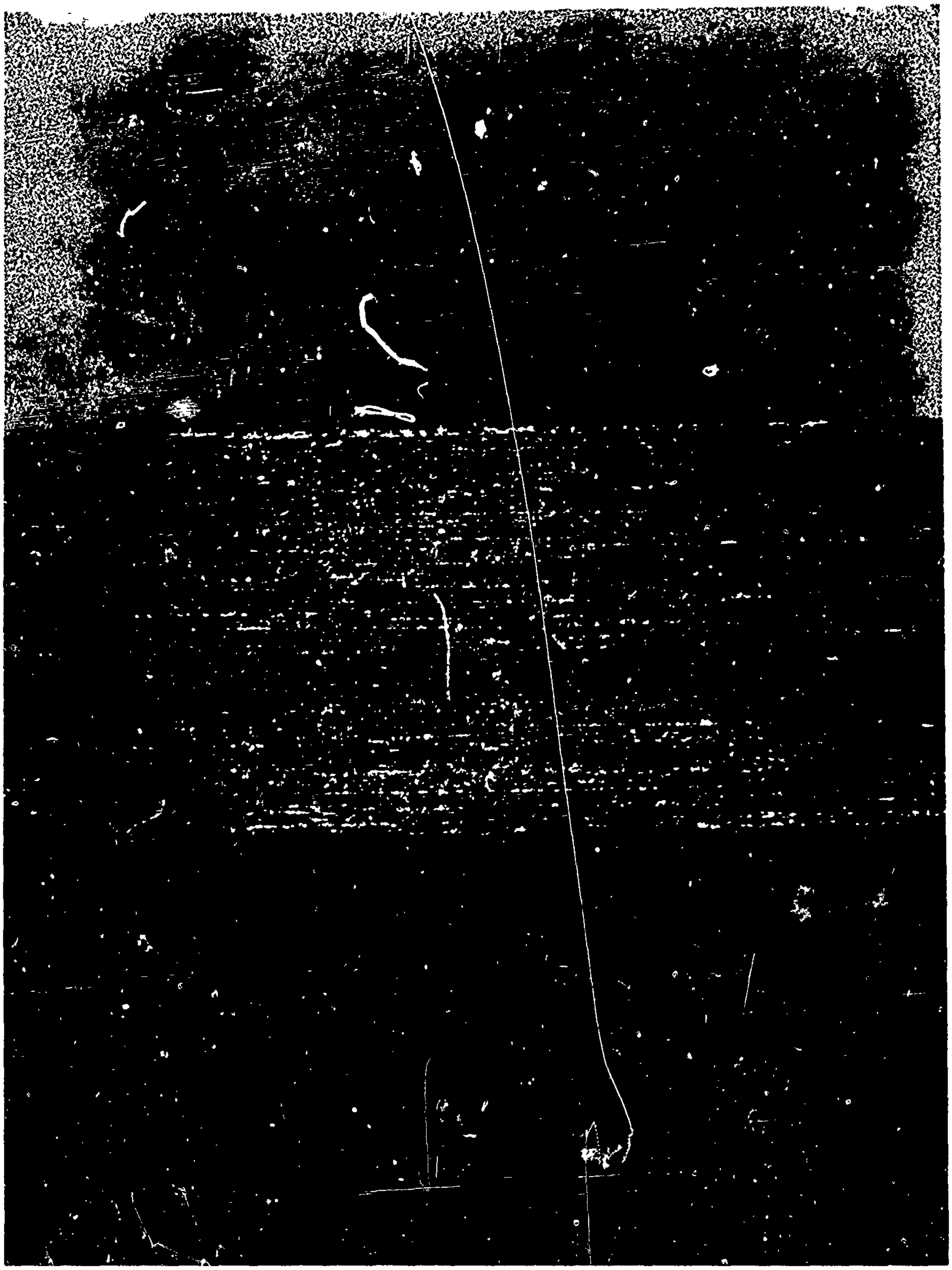


Figure 7-35. Cross Section of Piston Wall, Lower End (P-25190O)

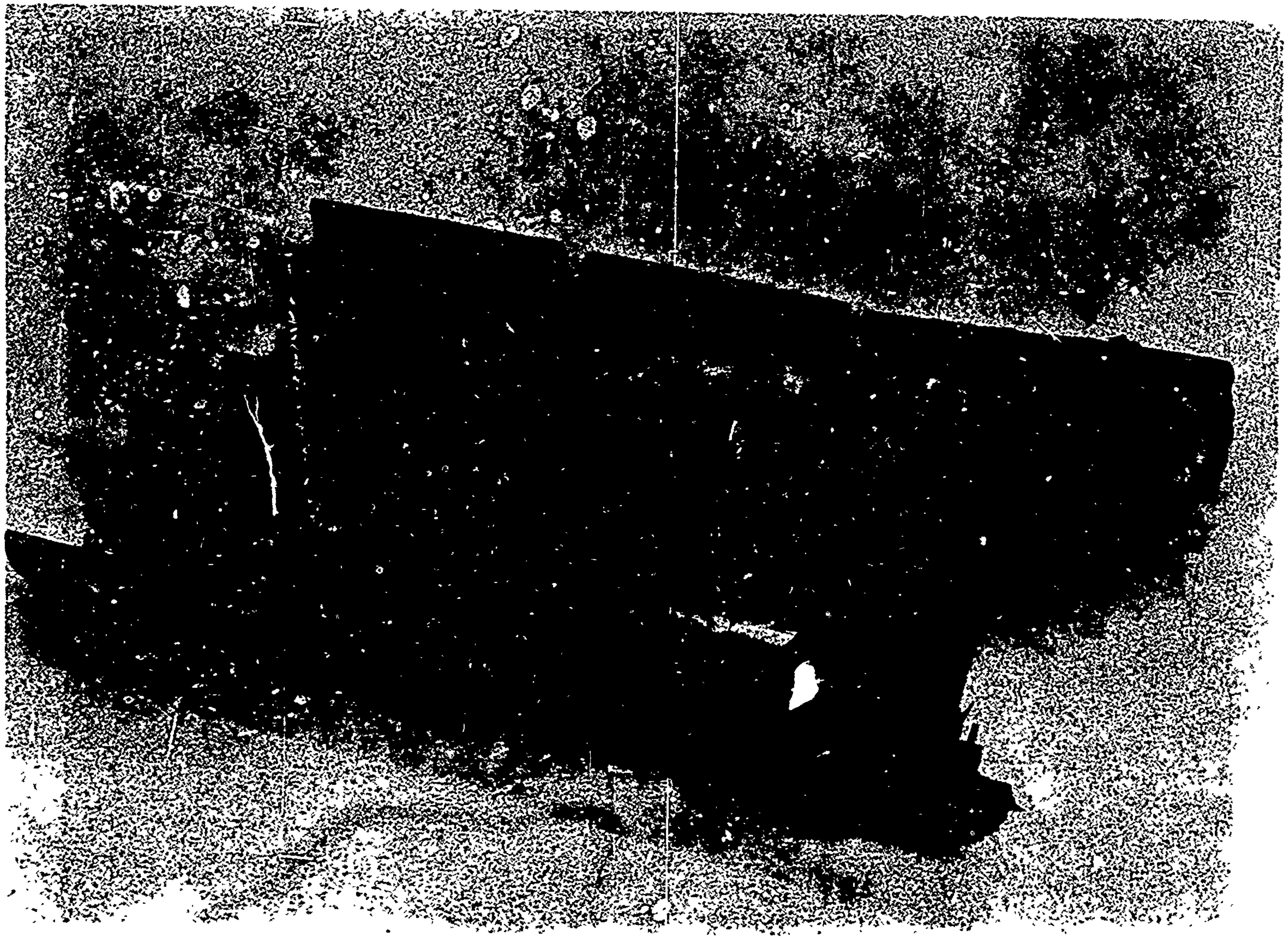


Figure 7-36. Sectioned Outer Cylinder (P-25190Z)

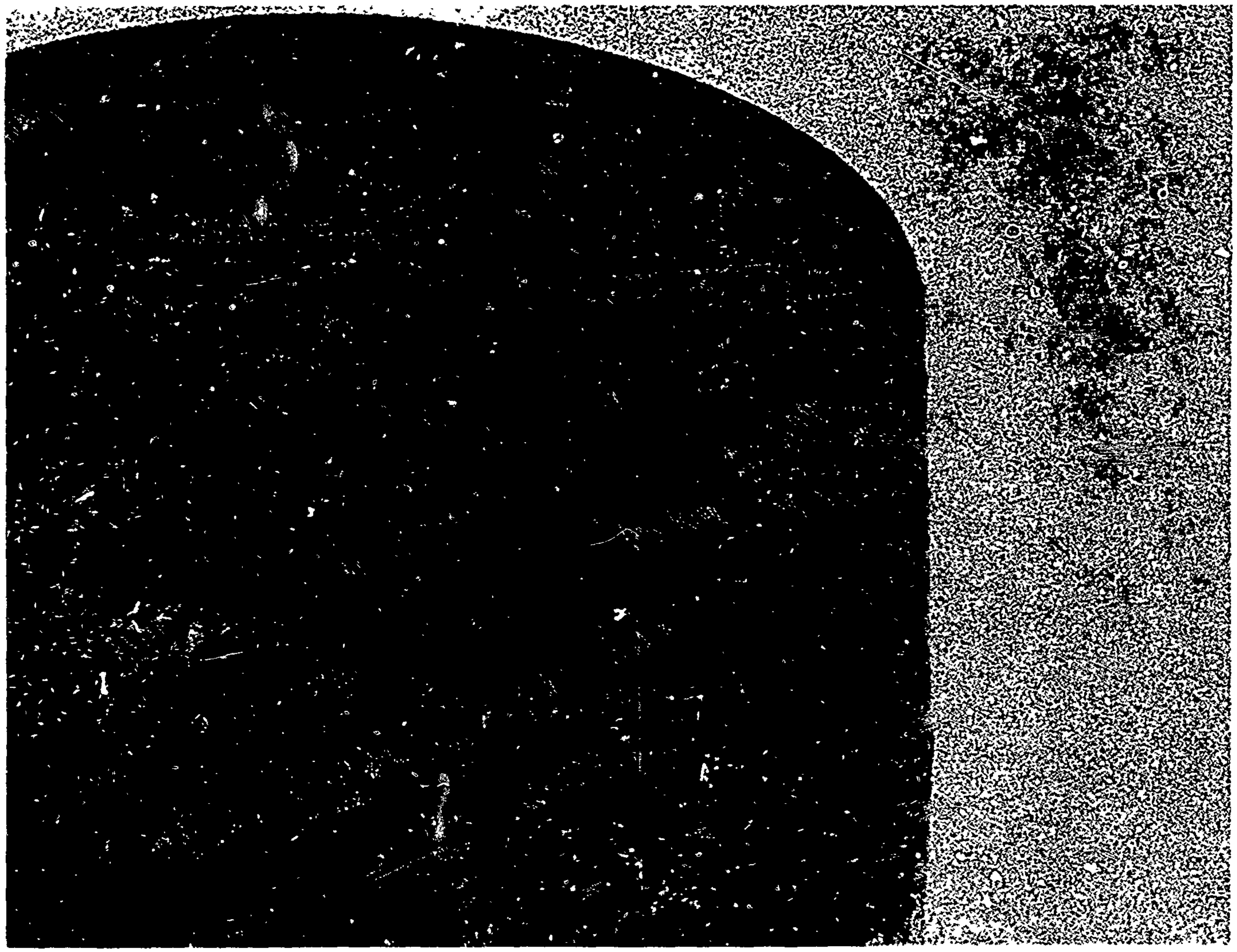


Figure 7-37. Cross Section of Outer Cylinder Wall (P-25190AA)

Figure 7-38. Cross Section of Piston Reinforcement (P-25190P)

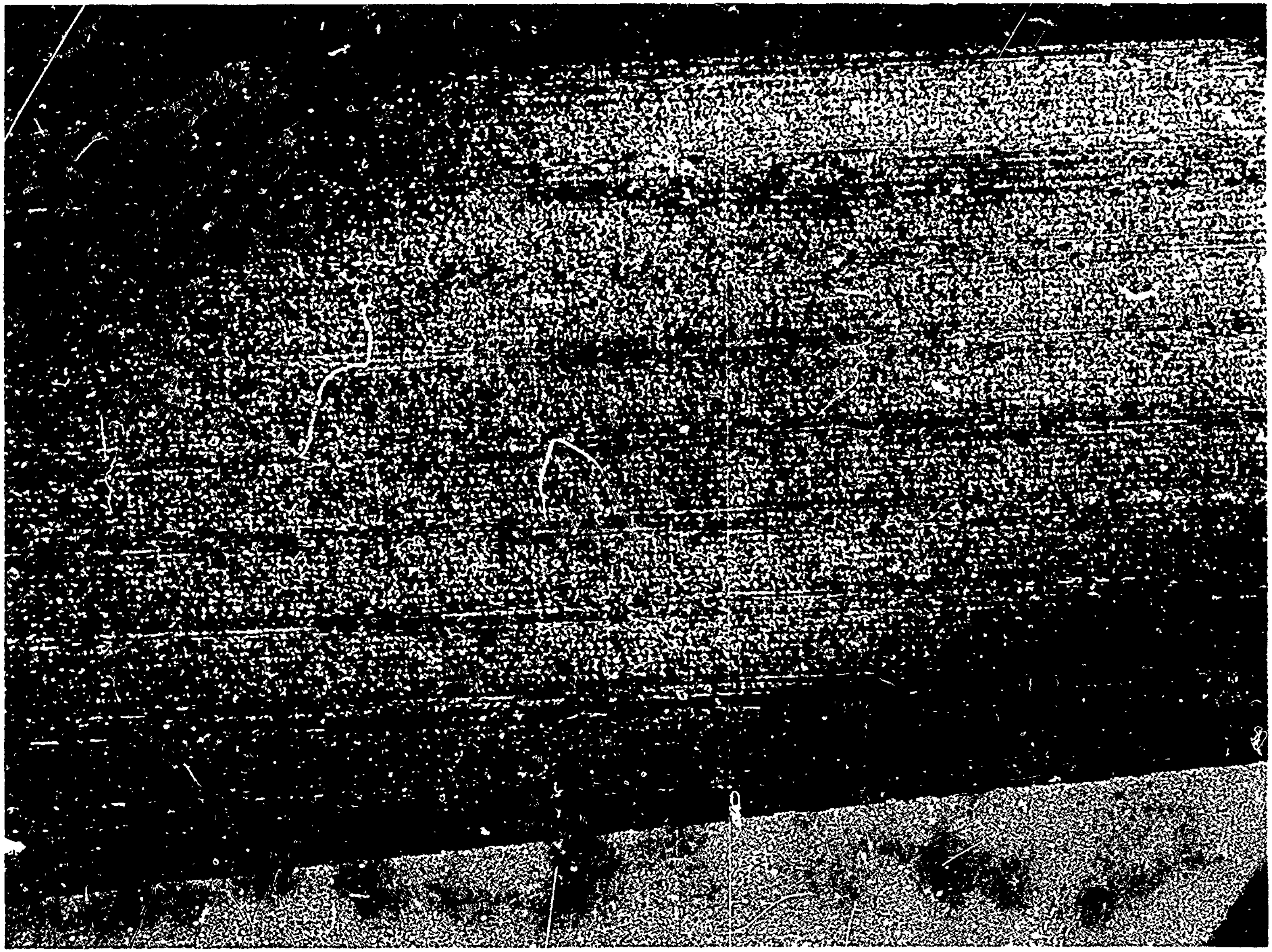


Figure 7-39. Cross Section of Piston Reinforcement (P-25190R)

7.3.1.4 Metallic Liners

Some problems were encountered with the outer and inner nickel liners applied to the shock strut cylinders. These fell into two categories: (a) liner quality and (b) bonding of the liners to the composite cylinders.

(a) Liner Quality

The inner liners in both cylinders appeared to be of sound quality. However, some difficulty was experienced in depositing a suitable outer liner on the piston cylinder. This particular liner was marked by the presence of cracks and a subsurface flaw (Figures 8-99 and 8-103).

Grade V nickel was specified for these liners (Paragraph 8.2.7). This is a relatively high strength nickel and was selected to resist yielding at the higher strains in the composite and to provide a hard stroking surface for the piston bearings. Perhaps the use of a softer, more ductile, nickel such as Grade I, would result in a crack-free deposition of metal. In addition, this grade may provide the remaining characteristics required of a suitable liner. Further experiments would be necessary to make this determination.

(b) Liner Bond

Little success was achieved during this program with bonding of the inner liners to the composite cylinders. Complete separation of the inner liner was experienced during fabrication (Figures 8-85 and 8-86). Examination of the sectioned outer cylinder (after structural testing) indicated poor adhesion of the inner liner to the composite cylinder. However, adhesion of the outer liner to the piston tube appears to have been relatively good.

(c) General

The problem of applying suitable metallic liners to composite parts appears to be a difficult one requiring further study. Efforts should also be made to develop suitable non-metallic coatings having the required wear, friction, and fluid resistant qualities.

7.3.2 Side Brace

Difficulties with the side brace assembly were associated with the conventional metallic fittings rather than the filament composite parts.

7.3.2.1 Structural Design - The first structural failure of the brace occurred in the upper links at a location just above the hinge pin, Figure 7-30. Failure was attributed to excessive deflection of the hinge pin which caused the axial loading to shift toward the inner edges of the composite members.

The design was constrained to using the same hinge pin specified for the conventional side brace currently used in the A37-B aircraft. This pin is a 260 ksi UTS pin which replaces an originally specified NAS (160 ksi) pin. The original pin displayed premature yielding during structural tests associated with the current aircraft.

There is, therefore, a history of a deflection problem associated with this particular joint in the conventional brace.

To produce a successful composite side brace would require a redesign incorporating a larger diameter, hollow, hinge pin. The stiffer pin would decrease joint deflections and promote a more evenly distributed load across the composite section.

This particular situation illustrates again the importance of considering localized effects when designing with composite materials. With the conventional side brace the ductility of the aluminum alloy components provides a redistribution of any localized over loads. With the linearity which characterizes a boron-epoxy composite, load concentrations remain localized and multiply directly up to the level which equals the rupture strength of the material.

The second structural failure occurred in the aluminum end fitting, Figure 7-32. This problem may be corrected by a simple redesign of the end fitting.

2. Fabrication - The processing procedures used in the fabrication of the side brace components resulted in good quality products. Compaction of the boron composite flanges appeared to be excellent and the adhesive bond between the flanges and the honeycomb core was sound. No structural problems were experienced during testing which could be attributed directly to the quality of the primary composite members.

### 7.3.3 Summary

This was the first attempt at designing and fabricating a variety of filament composite components intended for application in a fully functional landing gear assembly. Each component encompassed a number of structural design details and fabrication problems not previously attempted. The test results indicate that a relatively successful application of boron filament composites to the construction of a landing gear assembly was achieved. Strength levels between 98 and 150 percent of limit load were attained for the various loading conditions imposed.

This study has resulted in a considerable advance toward the application of filament composite materials in landing gear construction. Further work in the following areas is required to achieve completely satisfactory results in future applications to landing gear.

1. Fabrication of thick wall products.

2. The development of suitable liners and coatings for hydraulic cylinders.

3. The analysis and design of attachments and joints.